Optical Nonlinearities in Fibers: Review, Recent Examples, and Systems Applications

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***Abstract*—Optical nonlinearities give rise to many ubiquitous effects in optical fibers. These effects are interesting in themselves and can be detrimental in optical communications, but they also have many useful applications, especially for the implementation of all-optical functionalities in optical networks. In the present paper, we briefly review the different kinds of optical nonlinearities encountered in fibers, pointing out the essential material and fiber parameters that determine them. We describe the effects produced by each kind of nonlinearity, emphasizing their variations for different values of essential parameters. Throughout the paper, we refer to recent systems applications in which these effects have been dealt with or exploited.**

***Index Terms*—Optical communications, optical fibers, optical nonlinearities.**

I. Introduction

One of the unique characteristics of optical fibers is their relatively low threshold for nonlinear effects. This can be a serious disadvantage in optical communications, especially in wavelength-division multiplexing (WDM) systems, where many closely spaced channels propagate simultaneously, resulting in high optical intensities in the fiber. For instance, in a typical commercial 128-channel 10-Gb system, optical nonlinearities limit the power per channel to approximately -5 dBm for a total launched power of 16 dBm. Beyond this power level, optical nonlinearities can significantly degrade the information capacity of the system [1]–[3].

On the other hand, optical nonlinearities can be very useful for a number of applications, starting with distributed in-fiber amplification and extending to many other functions, such as wavelength conversion, multiplexing and demultiplexing, pulse regeneration, optical monitoring, and switching [4]. In fact, the development of the next generation of optical communication networks is likely to rely strongly on fiber nonlinearities in order to implement all-optical functionalities. The realization of these new networks will therefore require that one look at the tradeoff between the advantages and disadvantages of nonlinear effects in order to utilize their potential to the fullest [5].

Interest in nonlinear fiber optics developed with the rapid growth of optical-fiber communications in the early 1980s and has been strong for the past 25 years. Over that period, almost 4000 journal articles and 2500 conference papers have been published on the subject, several subfields have also developed and each of them has become very specialized. Therefore, it seems fitting to reexamine recent advances in the field in a broader and more fundamental context. Such a comprehensive approach has been taken in the excellent book by Agrawal [6], [7], initially published in 1989 and re-edited for the third time in 2001. The latter third edition contains additional material on fiber nonlinearities with short pulses, solitons and solitonic effects, and polarization aspects of fiber nonlinearities. The present journal review offers a more concise, but nevertheless comprehensive survey of the field of nonlinear fiber optics. It starts with a condensed review of basic optical nonlinearities in fibers, partially written in a tutorial style and with an emphasis on fundamentals. It also provides practical examples and numerous references. Accompanying the fundamentals, we have included references to the earliest observations of the various types of fiber nonlinearities. However, because of the extensive list of references already given in the book by Agrawal, the bulk of the references provided in the present review are from very recent studies. Besides a discussion of the nonlinear effects themselves, this review also covers new glasses and fiber geometries, with a special section on highly nonlinear fibers (HNLFs) and, in particular, microstructured fibers. We make a special effort to point out the impact of different fiber parameters related to both the material or glass composition and fiber geometry and the interplay between the two. Finally, we discuss the combined or joint effects of different nonlinearities acting simultaneously or concurrently [e.g., supercontinuum generation (SCG)]. This review should therefore be useful, not only to the general community of scientists and engineers who are interested in a brief but comprehensive overview of the field, but also to the practitioners or users of one or more of these nonlinearities, as a convenient resource providing basic formulas and characteristics as well as an extensive list of references. It can also serve as a primer to more specialized or fundamental treatments of the subject matter.

Why are optical nonlinearities so prominent in optical fibers?

It would in fact seem that, because of the small nonlinear index of silica ($n_2 = 2.6 \times 10^{-16}$ cm^2/W), these nonlinearities should be negligible. However, two characteristics of the fiber can strongly enhance optical nonlinearities: the core size and the length of the fiber. It is easy to show that the nonlinearities in bulk and silica fibers, respectively, are in the ratio [8]

$$\frac{I_{\mathrm{f}} L_{\mathrm{eff}}(\text{fiber})}{I_{\mathrm{b}} L_{\mathrm{eff}}(\text{bulk})} = \frac{\lambda}{\pi r_0^2 \alpha} \tag{1}$$

where $I_{\mathrm{f,b}}$ is the intensity (power per unit area) in the fiber and bulk, respectively, L_{eff} is the effective length, which for a long

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fiber is approximately equal to the inverse of the loss $(1/\alpha)$, λ is the wavelength, and r_0, the radius of the fiber core. As seen from (1), a small core radius and low loss can greatly enhance the efficiency of optical nonlinearities. As an example, if we choose the wavelength to be 1.5 μm, a fiber with a typical loss of 0.2 dB/km ($\alpha = 5 \times 10^{-5}\mathrm{m}^{-1}$), and a core radius of 8 μm, the nonlinear enhancement simply due to the small core can be of the order of 10^8.

When discussing nonlinearities, three fiber parameters are particularly important. The first two are the effective core area A_{eff} and the effective length L_{eff}

$$A_{\text{eff}} = \frac{\left\{ \int\limits_{-\infty}^{+\infty} |A(x,y)|^2 \, \mathrm{d}x\mathrm{d}y \right\}^2}{\int\limits_{-\infty}^{+\infty} |A(x,y)|^4 \, \mathrm{d}x\mathrm{d}y} \quad \text{and}$$

$$L_{\text{eff}} = \frac{1}{\alpha}(1 - \mathrm{e}^{-\alpha L}). \tag{2}$$

A_{eff} is the area the core would have if the optical intensity was uniformly distributed over it and zero outside (step function). Assuming the fundamental optical beam launched is Gaussian, it is given by $A_{\text{eff}} \sim \pi w^2$, in which the beam waist w can be calculated exactly. For conventional single-mode fibers, $A_{\text{eff}} \sim 80\ \mu\mathrm{m}^2$, for dispersion-shifted fibers (DSFs), it is $\sim 50\ \mu\mathrm{m}^2$, and for dispersion-compensated fibers, $\sim 20\ \mu\mathrm{m}^2$. L_{eff} is the length over which a signal would propagate through the fiber if it had a constant amplitude over that length and zero amplitude beyond ($L_{\text{eff}} = \int_0^L \mathrm{e}^{-\alpha l}\mathrm{d}l$). For a single-mode fiber with $\alpha = 0.2$ dB/km, $L_{\text{eff}} = 21$ km. The third parameter of great importance to optical nonlinearities in fibers is the group velocity dispersion (GVD) $\beta_2 \equiv -(\lambda^2/2\pi c^2)(\mathrm{d}n_{\mathrm{g}}/\mathrm{d}\lambda)$, in which $n_{\mathrm{g}} \equiv n - \lambda(\mathrm{d}n/\mathrm{d}\lambda)$ is the group refractive index and n, the normal index of refraction. The $\beta_2 > 0$ case corresponds to normal dispersion and $\beta_2 < 0$ to anomalous dispersion. In the normal dispersion regime, longer wavelengths travel faster, while in the anomalous dispersion regime, it is the shorter wavelengths that travel faster. In pure silica, $\beta_2 = 0$ at ~ 1310 nm, which is called the zero-dispersion wavelength (ZDW) λ_{ZDW}. In order to operate at the point of minimum loss in silica, as well as to satisfy phase-matching conditions for nonlinear effects, fibers are often fabricated with λ_{ZDW} near 1550 nm. This wavelength is also close to the maximum gain of erbium-doped fiber amplifiers (EDFA) at 1530 nm.

II. Optical Nonlinearities

A. General

The optical nonlinearities considered in this review are those that can give rise to gain or amplification, the conversion between wavelengths, the generation of new wavelengths or frequencies, the control of the temporal and spectral shape of pulses, and switching. They result from the interaction between several optical fields simultaneously present in the fiber and may also involve acoustic waves or molecular vibrations. One can distinguish two different types of nonlinearities [6], [7]:

I) the nonlinearities that arise from scattering [stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS)];

II) the nonlinearities that arise from optically induced changes in the refractive index, and result either in phase modulation [self-phase modulation (SPM) and cross-phase modulation (XPM)] or in the mixing of several waves and the generation of new frequencies [modulation instability (MI) and parametric processes, such as four-wave mixing (FWM)].

For both types of nonlinearities, the optical response of the material (static or dynamic) is modified by a large optical field. This material response can be represented by an expansion of the polarization [9]:

$$P = \chi^{(1)}E + \chi^{(2)}EE + \chi^{(3)}EEE \tag{3}$$

where $\chi^{(n)}$ is the nth-order susceptibility at optical frequencies. In glasses, because of the optical isotropy, the second-order susceptibility is zero, unless the glass has been poled. The various types of nonlinearities considered here can be expressed in terms of the real and imaginary parts of one of the nonlinear susceptibilities $\chi^{(n)}$ appearing in (3). The real part of the susceptibility is associated with the index of refraction and the imaginary part with a time or phase delay in the response of the material, giving rise to either loss or gain. For instance, the nuclear contribution to SRS or the electrostrictive stimulated Brillouin effect (both resulting in loss or gain) can be expressed in terms of the imaginary part of a $\chi^{(3)}$ susceptibility [10], [11], while FWM (a purely electronic and almost instantaneous effect resulting in frequency conversion) contributes to the real part of the $\chi^{(3)}$ susceptibility [12].

Since the present review is concerned with fibers, the nonlinearities discussed are essentially distributed, i.e., they are cumulative and further develop with distance along a length of the fiber. To ascertain the importance of a particular type of nonlinearity, it is therefore useful to estimate this length. Different lengths can be introduced that characterize the different contributions to the development of these nonlinearities. As we shall see, GVD directly affects the propagation of pulses and, therefore, the nonlinearities they can experience. For a pulse of initial input width τ_0, a dispersion length can be defined as $L_{\mathrm{D}} \equiv \tau_0^2/|\beta_2|$. If the pulse is initially Gaussian, its width $\tau(z)$ can be shown to increase with z as $\tau(z) = \tau_0[1 + (z/L_{\mathrm{D}})^2]^{1/2}$ [13]. The second length is the nonlinear length, L_{NL}. Nonlinearities are usually triggered by changes initiated in the propagating medium by a pump copropagating with a signal. However, as the pump propagates, it also progressively loses power and becomes depleted, no longer acting as a pump. It is therefore useful to define a nonlinear length over which the pump is effective in providing energy or gain, $L_{\mathrm{NL}} = (GP)^{-1}$, in which G is the gain, and P is the pump power. When considering phase-matched nonlinearities, one also needs to define the length over which several copropagating lightwaves lose their mutual phase coherence, $L_{\mathrm{c}} = 2\pi/|\kappa|$, in which κ is the phase mismatch. Finally, when considering polarization effects, it is necessary to define the polarization beat length, $L_{\mathrm{B}} = 2\pi/|n_x - n_y|$, in which $n_{x,y}$ are the indices of refraction along

x and y, respectively. This is the length over which a phase difference of 2π develops between the x and y field components of the light. In the following, the dominant contributions to the development of nonlinear effects come from those for which the corresponding characteristic length is the shortest. For instance, $L_{\rm D} \ll L_{\rm NL}$ indicates that the optical nonlinearities considered are developing over a much longer length than the length over which a pulse broadens because of its GVD. Hence, dispersion must be taken into account when describing these nonlinearities (dispersion-dominated regime). Similarly, $L_{\rm B} \ll L_{\rm NL}$ would indicate that polarization effects will strongly influence the development of nonlinearities (polarization-dispersion-dominated regime). It should, however, be obvious that the different contributions described here are only important when the corresponding lengths are comparable or shorter than the effective length $L_{\rm eff}$ of the fiber. If these lengths are much longer, then the corresponding effects can be ignored.

B. Scattering Nonlinearities

Type I) nonlinearities involve the lattice or vibrational dynamics (nuclear contribution) of the glass and must, therefore, satisfy the laws of conservation of both energy and momentum of the light and lattice taken together

$$\Omega = \omega_{\rm L} - \omega_{\rm S} \quad \text{and} \quad \vec{q} = \vec{k}_{\rm L} - \vec{k}_{\rm S} \tag{4}$$

where L and S stand for laser and Stokes, respectively, ω and k are the frequency and wavevector of the light, and Ω and q, those of a lattice phonon. In SBS, the scattered or Stokes light is downshifted by the frequency of an acoustic phonon ($\sim$ 10 GHz), and in SRS, by the frequency of an optic phonon or molecular vibration. In silica, the SRS gain is maximum at $\Omega = 13.2$ THz from the laser line [14], which corresponds to the dominant Raman band, called the "broadband." From the combination of the two conservation laws, and considering the fact that acoustic frequencies are much lower than optical frequencies, one can easily show that SBS occurs at relatively low powers and is maximum in the backward direction and zero in the forward direction. This explains why SBS can be so detrimental in optical communications and is usually avoided by keeping the power per channel below the threshold. In cases where the powers needed are higher than the threshold, dithering or phase modulation of the laser can be used. Such a phase modulation at frequencies of a few hundred megahertz broadens the laser linewidth, effectively suppressing the SBS [see (6) below]. On the positive side, SBS can be exploited in ultranarrow linewidth lasers and for remote sensing, as discussed below. The case of SRS is different, because the light and the optic phonon are much closer in frequencies. In that case, the scattering cross section exhibits a much smaller angular dependence, especially for an isotropic medium such as glass, and Raman scattering can be observed in the forward and backward directions, albeit slightly more efficiently in the forward direction [15].

When discussing scattering nonlinearities, particularly in the context of optical communications, it is important to emphasize that this scattering is stimulated and not simply spontaneous. While, in the spontaneous regime, the light scattering originates from thermally populated phonons or vibrations that are characteristic of the medium and not influenced by the light, in the stimulated case, the light itself creates these phonons and subsequently scatters from them. The single most important difference between the spontaneous and stimulated regimes is that, in the former, the thermally populated phonons are incoherent, while in the latter, the light coherently creates phonons, thereby rendering the stimulated processes much more efficient. The threshold for stimulated processes is that input power for which phonons are created at a higher rate than the rate at which they are annihilated. It can be expressed as [16]

$$P_{\rm th} = \frac{C A_{\rm eff}}{g L_{\rm eff}} \tag{5}$$

where $A_{\rm eff}$, $L_{\rm eff}$, g, and C are, respectively, the effective modal area, the effective length defined earlier, the gain coefficient, and a constant that depends on the particular process. For SBS in single-polarization fibers, $C \approx 21$ and $g_{\rm B} \sim 5 \times 10^{-11}$ m/W, and for SRS, $C \approx 16$ in the forward direction ($C \approx 20$ in the backward direction) and $g_{\rm R} \sim 1 \times 10^{-13}$ m/W [16]. Using the same parameters as earlier ($\alpha = 0.2$ dB/km, $L_{\rm eff} = 21$ km, and $A_{\rm eff} = 80$ μm^2), the thresholds for SBS and SRS are found to be approximately 2 dBm (1.6 mW) and 28 dBm (700 mW), respectively. In practice, variations in core size along the fiber and other inhomogeneities tend to raise the SBS threshold to higher powers, between 5 and 10 dBm (3–10 mW) for SBS and between 28 and 32 dBm (0.7–1.17 W) for SRS. However, these powers are commonly reached in fibers so that SBS and SRS nonlinearities are often encountered in optical communications and can be exploited for practical purposes.

SBS and SRS can be generated from noise by a pump or seeded by a signal in the presence of a pump. In the first case, the particular Stokes wave that is shifted from the incident beam by exactly the frequency of an acoustic or optic phonon is preferentially amplified. In the second case, the pump transfers energy to the signal, which seeds the Stokes wave and is thereby amplified. In this case, the threshold will also depend on the relative polarizations of the pump and signal and may be a factor of one to two greater than as given in (5).

As was mentioned in the previous section, for two waves to interact through a nonlinear process, both must propagate at the same velocity, which also means that their phases must be matched. In addition, when pulses are involved, their GVD must be close to each other. For SBS in fibers, phase matching between the pump and a particular Stokes wave occurs because of the availability of a broad spectrum of acoustic phonons, with $\omega \propto q$, only one of which satisfies the conservation laws [see (4)] in the backscattering geometry. For SRS, phase matching occurs "automatically" over a broad range of frequencies because of the very broad spectrum of molecular vibrations in silica glass [17]. For the reasons just mentioned, these scattering nonlinear processes are often said to be self-phase-matched. This is not the case for the parametric processes discussed later in this paper. Next, we examine successively the specific aspects and manifestations of SBS and SRS.

1) Stimulated Brillouin Scattering (SBS): In SBS, the Stokes wave is backscattered while the photogenerated acoustic wave propagates collinearly with the incident pump beam [18]. At the onset of SBS, the reflected light increases rapidly with incident optical power and the transmitted light eventually saturates. The threshold for SBS is particularly low, because the gain coefficient is relatively high when compared to other nonlinearities such as SRS. The effective Brillouin gain coefficient is given by

$$\widetilde{g}_{\mathrm{B}} = \frac{\Delta\nu_{\mathrm{B}}}{\Delta\nu_{\mathrm{B}} + \Delta\nu_{\mathrm{s}}} g_{\mathrm{B}}(\nu_{\mathrm{B}}) \tag{6}$$

where $g_{\mathrm{B}}(\nu_{\mathrm{B}})(\sim 5 \times 10^{-11}$ m/W) is the maximum Brillouin gain obtained for a perfectly monochromatic signal and $\Delta\nu_{\mathrm{B}}$ and $\Delta\nu_{\mathrm{s}}$, the spectral widths of the Brillouin and signal beams respectively. The Brillouin gain can thus be reduced or, equivalently, the threshold raised by increasing the spectral width of the signal beam through dithering, as indicated in the previous section. Another technique used to mitigate SBS is the application of RF tones to the signal, which redistributes the power over several sidebands. Concurrently with the development of new schemes to minimize SBS, new fiber structures are being investigated. A new dispersion-decreasing fiber was recently designed and fabricated that showed a 7-dB increase in the threshold over conventional fibers [19]. The decreasing dispersion is achieved through a progressive reduction of the core radius along the fiber. A similar result can be obtained by introducing a GeO_2 concentration gradient along the fiber [20]. Even more promising are the photonic crystal fibers (PCFs). These have been shown to exhibit SBS thresholds as high as 18 or 20 dBm [21]. The fundamental reason for the higher SBS thresholds of these new fibers may be a lower degree of overlap between the acoustic and optic modes. Indeed, (5) assumes perfect overlap between the two, which only happens for very special index profiles.

Although dominated by one major peak due to the longitudinal acoustic wave, the SBS spectrum usually shows other peaks as well, reflecting the presence of several acoustic modes [22], [23]. This is particularly true for small core fibers, in which the finite numerical aperture can result in acoustic diffraction and the generation of both longitudinal and transverse modes [24]. The influence of acoustic diffraction on nonstationary SBS in small core fibers can also lead to new dynamical effects, such as the generation of a stable train of compressed pulses [25]. This effect appears to be related to an MI that is transferred from the pump to the Brillouin Stokes wave, creating backward-propagating Brillouin solitons [26]. The original aspect of this Brillouin-soliton generation is that it can occur even in the absence of dispersion (GVD, $\beta_2 = 0$) because it relies on the presence of a solitary acoustic wave [27]. It also gives rise to both forward and backward scattering (FSBS). A similar SBS-driven effect may be at work in the generation of short optical pulses from a phase-modulated continuous-wave (CW) beam [28]. Related effects to the one described above have been proposed to control the speed of light in a fiber [29] and for an active-fiber delay line [30].

Another common application of SBS is that for narrow-linewidth amplifiers [31] and lasers [32], [33]. An original implementation of a Brillouin laser has been proposed and demonstrated in an erbium-doped fiber [34]. There, the combination of SBS and erbium gain leads to the appearance of strong higher order Stokes waves [35] or a comb of frequencies with $\sim$ 10-GHz line spacing [36]. Applications to microwave photonics have also been proposed [37], [38].

Polarization plays an important role in SBS, as well as in the other nonlinearities discussed in this paper. The interaction of two optical modes is minimized when the two modes have orthogonal states of polarization (SOP) [39]. Therefore, one way to mitigate SBS is to multiplex two equivalent signals with orthogonal SOP, each with half the total launched power desired. It is worth noting, however, that these two polarizations can still interact and generate SBS, albeit less effectively, since it involves the electrostriction tensor that has off diagonal as well as diagonal terms. One can show that mixing two "half-signals" with orthogonal SOPs raises the effective threshold by $\sim$ 1 dB [40]. If, in addition, the two half-signals are shifted in frequency relative to each other by more than the Brillouin width $\Delta\nu_{\mathrm{B}}$, the effective threshold is then raised by the full 3 dB (or a factor of 2).

With the Stokes wave being backscattered, SBS can also be used for remote time-domain reflectometry [41]. In this latter application, a CW probe and a pulsed pump are counter-propagated in the fiber, with the probe downshifted by the Brillouin frequency acting as the Stokes wave. Any mechanical change in the fiber can then be detected from the corresponding change noted in the Stokes signal, and the location of this change can be determined remotely by its arrival time. Because of the polarization dependence of the SBS gain, this technique can also be used to determine the SOP of the light at any point along the fiber [42].

2) Stimulated Raman Scattering (SRS): SRS differs from SBS in three ways. First, due to the lower Raman-gain coefficient $g_{\mathrm{R}} \sim 1 \times 10^{-13}$ m/W, SRS occurs at much higher powers than SBS, which are typically greater than $\sim$ 1 W [43]. Second, the Raman shift, $\sim$ 13.2 THz in silica, is much greater than the Brillouin shift. Thirdly, SRS generates a Stokes beam both forwards and backwards, although more efficiently in the forward direction [15]. Over the past 10 years, SRS has been of particular interest for fiber amplifiers and lasers. It has also been exploited for several other applications, such as wavelength conversion, optical modulation, and switching. Finally, combined with parametric nonlinearities, it can give rise to a variety of optical effects, such as ultrashort pulse or SCG. We discuss these different applications in turn.

Raman fiber amplifiers offer two significant advantages over EDFAs [44]. The first one is that the maximum gain is obtained at a frequency shift that is relative to the wavelength of the pump laser and not at a fixed absolute frequency [45]. The latter can therefore be chosen to provide maximum gain in any desired wavelength range, S-, C-, or L-band. Second, the gain bandwidth is much greater than that provided by EDFAs (> 100 nm versus 35 nm) and can be further widened by a proper choice of the fiber-material composition. Although the SRS gain curve is not really flat over the 100 nm or so bandwidth available, it can be made flat within 1–2 dB in several ways. The first and passive way is to introduce a wavelength-selective loss and artificially clip the higher gain central portion of the curve. A second way is to use several pumps at staggered wavelengths, so that the gain curve of each one complements the gain curves of the others [46]. In a more sophisticated version of this second scheme, called dynamical gain flattening, the pump powers are constantly adjusted in order to respond to variations in signal intensity in a particular wavelength range and maintain a constant overall gain. This is particularly important in WDM systems in which the gain in any particular wavelength range can be significantly affected when channels are added or dropped in that range.

SRS can be used for lumped as well as distributed amplification in communication systems [47]. In the lumped mode, amplification is provided by about 80 m of a small core fiber inserted in the system as a distinct unit and pumped separately. In the distributed mode, the transmission fiber itself is used as the gain medium. Through SRS, power is progressively transferred from shorter wavelengths to longer ones (Stokes process) over the characteristic Raman-gain length $L_{\mathrm{G}} = (g_{\mathrm{R}} P/A_{\mathrm{eff}})^{-1}$. After this length L_{G}, the pump has transferred most of its power to the signal, which then progressively attenuates itself along the remainder of the fiber. This may result in a low signal power and poor performance at the receiver end. Therefore, a combination of pumps is often used in fiber optic links, some copropagating and the others counterpropagating with the signals, to optimize the optical-signal-to-noise (OSNR) ratio at the receiver. Simultaneously pumping from both ends of the fiber span also provides better results in terms of gain flatness. One drawback of the copumping scheme is the transfer of relative intensity noise (RIN) from the pump laser to the Stokes signal [48], [49].

A particular aspect of distributed Raman amplification in WDM systems is the transfer of energy from channels at shorter wavelengths (higher frequencies) to channels at longer wavelengths within the gain bandwidth. This introduces a positive tilt in the powers of successive channels [50]. The gain in different parts of the spectrum must therefore be adjusted in order to compensate for this tilt and ensure equal channel power at the receiver input. This can be achieved by introducing, at an appropriate point in a fiber span, a broadband filter with a negative tilt, or a high-pass filter [51], [52]. A comprehensive analysis and design methods are presented in [47].

SRS gain is also being extensively used in a cavity configuration for laser applications. A Raman fiber laser consists of a Raman active fiber (usually a small-core HNLF) placed between two sets of cascaded Bragg gratings. Each grating pair defines a cavity that lases at a particular Stokes wavelength, and successive gratings reflect light from increasingly higher Stokes orders. As an example of a Raman fiber laser [53], an initial pump beam is generated at $\sim$ 1050 nm in an ytterbium-doped fiber and launched into a phosphate fiber with first Stokes light at $\sim$ 1210 nm. From successive conversion to as high as the fifth- or sixth-order Stokes, it is possible to generate output light at 1550 nm. A pair of gratings ensures sufficient gain at each successive Stokes wavelength. As was mentioned earlier, SRS provides much more flexibility than erbium-stimulated emission in the design of a laser, since the wavelength of the light generated is only relative to the wavelength of the pump, which can be chosen at an appropriate position. Another important point that should be mentioned is that, although the intrinsic threshold for SRS is relatively high for a single pass, as in an amplifier, it can be much lower in a laser-cavity configuration because of multiple passes of the beam through the Raman-gain medium [54].

From the very fact that SRS provides gain at a wavelength that is shifted from the pump by a significant $\Delta\lambda$ ($\sim$ 13 THz or $\sim$ 100 nm at 1550 nm and $\sim$ 75 nm at 1300 nm in silica), it can also be used for wavelength conversion from an initial signal to a probe. One realization of this application consists in copropagating, in an HNLF, a strong signal modulated by the data stream and a CW probe upshifted from it by the Stokes frequency ($\sim$ 13 THz). Due to the Raman effect, the upshifted or shorter wavelength probe is depleted at the benefit of the (Stokes) signal. Since the Raman-mediated power transfer is a function of the signal power, the negative or complementary of the data stream carried by the signal is transferred to the probe [55]. A similar scheme can be used for all-optical switching or modulation. In this case, the situation is reversed. The above (Stokes) probe becomes a control beam to which the signal can transfer energy and the presence or absence of the control beam allows switching [56] or modulation of the pump [57].

The SRS applications discussed above have been under the condition of CW or quasi-CW pump beams. There is, however, a growing interest in the SRS of pulsed beams, in particular for applications to high-power fiber amplifiers and lasers. When using short pulse pumps, two additional effects must be considered. The first one is the walk-off effect between the pump and the SRS-generated Stokes pulse. For very short pump pulses, the walk-off length can be significantly shorter than the length of the fiber, which can limit the efficiency of the Raman process. Another difference is the combination of SRS with other nonlinearities (higher order nonlinear effects) [58], [59]. One of the most important of these higher order effects is intrapulse Raman scattering, a combination of SRS and SPM or XPM that can lead, in the anomalous dispersion regime, to the formation of very short pulses or Raman solitons [60] and to subsequent self-frequency shifts [61], [62]. This higher order effect can be used to generate subpicosecond Stokes soliton pulses that are both tunable in frequency and in duration [63]. If instead of a single pump pulse, a train of such pulses is copropagated along with a CW signal, the combined effects of SRS and XPM result in a train of ultrashort signal pulses that can even be much shorter than the pump pulses [64]. The combined effects of SRS and MI can also lead to the formation of very-short pulses or solitons [65], [66]. As a final example, SRS and parametric FWM between a pump and a Stokes wave can generate the anti-Stokes wave or, equivalently, two pump photons can simultaneously generate a Stokes and an anti-Stokes photon, as described in the next section on $\chi^{(3)}$ nonlinearities. Recent measurements of the dependence of SRS on chromatic dispersion have revealed a threefold increase in Raman gain due to the added contribution of FWM under phase-matching conditions [67]. With high-power picosecond pulses, this SRS–FWM nonlinear process is also responsible for the generation of a broad continuum of wavelengths (see discussions on supercontinuum below).

Besides conventional silica fibers, new high Δn fibers are being developed for Raman applications, especially germanosilicate and phosphosilicate fibers [68] and bismuth-doped silica fibers [69]. Non-silica glasses and fibers are also being investigated for providing enhanced Raman gain over an extended wavelength range. Tellurite fibers are particularly attractive because of the greater refractive index of TeO_2 (2.3–2.4) combined with its excellent chemical and physical glass properties [70], [71]. Other promising candidates are chalcogenide (As–Se) glasses and fibers (see Section III). For example, in a small core As–Se fiber, a Raman coefficient 300 times greater than that of silica has been measured, giving more than 20 dB of gain in a 1.1-m length [72]. However, the attractiveness of the superior nonlinear optical properties of chalcogenide fibers is somewhat moderated by the lesser chemical stability of the glass.

C. $\chi^{(3)}$ Nonlinearities

Type II) nonlinearities are often referred to as $\chi^{(3)}$ nonlinearities. They arise from light-induced (nonlinear) changes in the index of refraction and can result in nonlinear refraction (Kerr effect) or the mixing of optical beams (parametric interactions).

These nonlinearities are essentially based on the light-induced nonlinear electronic polarization of the medium. The refractive index can be expressed as

$$n = n_0 + n_2 I \tag{7}$$

where n_0 is the linear index, n_2 the nonlinear coefficient, and I is the optical intensity. In silica, $n_2 \approx 2.6 \times 10^{-16}$ cm^2/W. The third-order susceptibility is related to n_2 by [73]

$$n_2 = \frac{3}{8n_0}\mathrm{Re}\left(\chi^{(3)}\right). \tag{8}$$

Practically, the coefficient that determines the magnitude of the corresponding nonlinear effects is

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{\mathrm{eff}}} \tag{9}$$

where λ is the free-space wavelength and A_{eff} is the effective core area. For a typical single-mode silica fiber, $\gamma \sim 20\ \mathrm{W}^{-1}\mathrm{km}^{-1}$. The result of these nonlinearities is to introduce a nonlinear shift in the phase of the propagating light

$$\phi_{\mathrm{NL}}(z) = \gamma P_0 z \tag{10}$$

where P_0 is the peak input power and L_{eff} the effective length given earlier. The nonlinear phase change can also be rewritten in terms of a nonlinear length $L_{\mathrm{NL}} \equiv (\gamma P_0)^{-1}$:

$$\phi_{\mathrm{NL}} = \frac{z}{L_{\mathrm{NL}}}. \tag{11}$$

For a 1-mW input power at $\lambda = 1.55\ \mu$m in a single-mode fiber with $A_{\mathrm{eff}} = 50\ \mu\mathrm{m}^2$, $L_{\mathrm{NL}} \approx 500$ m. This illustrates the importance of these nonlinearities on the propagation of optical signals in optical communications systems [1]. Their impact can be particularly significant in WDM systems, in which the total power integrated over all channels can reach 15 dBm or more ($\sim$ 30 mW) at any point in the fiber [2], [3]. Because the optical power can have a spatial as well as time dependence, $\chi^{(3)}$ nonlinearities can modify the mode-field distribution, as well as give rise to a variety of changes both in pulse shape (time domain) and in spectral content (frequency domain).

$\chi^{(3)}$ nonlinearities can be divided in two groups: SPM and XPM in one; and parametric processes, such as FWM and third harmonic generation (THG) in the other.

SPM, XPM, and FWM have a common origin, which can be shown mathematically by considering the interaction of two beams. The total electric field can then be written as

$$E(r,t) = \frac{1}{2}\left[E_1 \exp(-i\omega_1 t) + E_2 \exp(-i\omega_2 t)\right] + c \cdot c. \tag{12}$$

Then, substituting in (3) produces a variety of P_{NL} terms:

1) $P_{\mathrm{NL}}(\omega_1) \propto (|E_1|^2 + 2|E_2|^2)E_1$ and $P_{\mathrm{NL}}(\omega_2) \propto (|E_2|^2 + 2|E_1|^2)E_2$ contain both SPM (first term in each) and XPM (second term in each);
2) $P_{\mathrm{NL}}(2\omega_1 - \omega_2) \propto E_1^2 E_2^*$ and $P_{\mathrm{NL}}(2\omega_2 - \omega_1) \propto E_2^2 E_1^*$ represent the FWM terms.

In the following, we present the specific aspects of each of these nonlinearities successively, first describing their effect on the guided propagation of light, then giving examples and references to recent applications, especially in optical communications.

1) Self-Phase Modulation (SPM): In SPM, the intensity modulation of an optical beam results in the modulation of its own phase via modulation of the refractive index of the medium. The resulting time-dependent change, or modulation of the phase, leads to spectral broadening or frequency chirping [74]

$$\Delta\omega(z,t) = -\frac{\partial\phi_{\mathrm{NL}}}{\partial t} = -\frac{2\pi n_2}{\lambda A_{\mathrm{eff}}}\frac{\mathrm{d}P(t)}{\mathrm{d}t}z = -n_2\frac{\mathrm{d}I(t)}{\mathrm{d}t}kz \tag{13}$$

where I is the optical intensity, k and λ the wavevector and wavelength respectively, P the optical power, and A_{eff} the effective mode area given above. Because of the time derivative in (13), it is clear that SPM is essentially a pulse effect, with the leading edge of the pulse being red-shifted and the trailing edge blue-shifted. In addition, the pulse spectrum exhibits characteristic oscillations, which are due to the interference, within the pulse, of component waves with the same frequency but different phases. The nonlinear spectral broadening can be either compensated or magnified by the chromatic dispersion of the fiber. In the normal chromatic-dispersion regime ($\lambda < \lambda_{\mathrm{ZDW}}$), in which red light travels faster than blue light, the nonlinear dispersion is magnified by the chromatic dispersion, resulting in enhanced broadening. In the anomalous dispersion regime ($\lambda > \lambda_{\mathrm{ZDW}}$), the nonlinear dispersion is compensated, leading to pulse compression or, when exactly balanced, to the formation of solitons [75].

From the previous description, the net effects of SPM can be seen to depend essentially on the characteristics of the initial pulse, its temporal shape, spectrum, and initial chirp, to which one must add the effect of chromatic dispersion. The shorter the pulse, the shorter the dispersion length L_{D}, and the more important GVD becomes. With appropriate dispersion and pulse characteristics, SPM can be used for the spectral and temporal compression of pulses, soliton generation and pulse regeneration. In the following, we give further explanations on these applications and cite recent examples.

Spectral compression of a pulse can be achieved through SPM, provided the initial pulse is negatively chirped. In that case, the higher frequency components at the leading edge of the pulse are being red-shifted by SPM, while the lower frequency components at the trailing edge of the pulse are simultaneously being blue-shifted, thus canceling the initial chirp of the pulse. As an example, spectral compression from 8.4 to 2.4 nm of negatively chirped pulses has been reported, with a constant phase over the spectral and temporal envelopes, characteristic of near-transform-limited pulses [76]. This spectral-compression method has also been applied in fiber amplifiers to obtain picosecond pulses with peak powers of several kilowatts [77]. A general theoretical treatment is given in [78].

Temporal pulse compression is usually achieved in two stages. In the first stage, a pulse is spectrally broadened and linearly chirped through SPM in the presence of normal dispersion. In the second stage, the frequency components of the chirped pulse are temporally compressed in a section of fiber with anomalous dispersion. The temporal pulse-compression part can also be achieved with a prism or a grating pair. Another scheme has also been proposed, using an unchirped apodized fiber Bragg grating as the nonlinear dispersive element in the first stage of the compressor [79]. The compression is then due to the strong dispersion of the Bragg grating at frequencies close to the edge on the long-wavelength side of the photonic bandgap, where the transmission is still high. With this second scheme, pulse compression can be achieved over shorter lengths and with fewer constraints. System examples of pulse compression are presented in [80] and [81], showing a pulse broadening and recompression ratio greater than 300 over a 2.5-km transmission link. One of the choices in pulse compression is whether to pre- or post-compensate the chromatic dispersion (i.e., before or after the SPM). A comparison of both methods suggests that SPM is more effective in the post-compensated links, resulting in stronger pulse narrowing and yielding a low eye-opening penalty, which is, moreover, power independent over a wide range of powers [80], [82].

Pulse compression is also an integral part of the pulse-regeneration process in optical communication networks, which includes retiming, recompression, and reamplification (3R). 3R regeneration can be achieved by synchronous modulation, SPM in an HLNF section, narrowband filtering or slicing and finally Raman or parametric reamplification [83]. Filtering is used if the fiber has anomalous dispersion, and slicing if it has normal dispersion. Slicing is better able to stabilize the amplitude of the pulse but requires a higher signal power in the fiber.

SPM in the anomalous dispersion regime can also lead to two other nonlinear effects, MI and soliton generation. MI leads to the breakup of a CW wave into a train of very narrow pulses [84]. It occurs when the CW lightwave is subjected to a small periodic perturbation with frequency Ω and wavevector K. Starting from the nonlinear Schrodinger equation containing an SPM term, one can show that the wavevector of the perturbing wave becomes imaginary for perturbation frequencies $\Omega < \Omega_{\mathrm{c}}$, with Ω_{c} given by [7], [85]

$$\Omega_{\mathrm{c}}^2 = \frac{4\gamma P_0}{|\beta_2|} = \frac{4}{|\beta_2| L_{\mathrm{NL}}} \tag{14}$$

in which β_2 is the GVD. The perturbation introduces a dynamical modulation of the nonlinear self-phase shift and a periodic chirp of the CW beam. Under the influence of the GVD, this periodic chirp leads the breakup of the CW beam into a train of ultrashort pulses with a repetition rate equal to Ω. The fastest growth of these pulses or the maximum MI gain occurs for $\Omega_{\max} = \Omega_{\mathrm{c}}/\sqrt{2}$. However, different dispersion profiles can modify the MI gain significantly. For instance, the MI gain spectrum has been shown to be much broader in dispersion-decreasing fibers than in conventional fibers [86]. As for SBS and SRS, MI can also be initiated by noise. In that case, the noise component at frequency $\Omega_{\max}$, having the maximum gain, grows preferentially. In optical transmission systems with RIN and amplified-spontaneous-emission (ASE) noise, such a noise-generated MI can impair the performance of the system if the dispersion of the fiber is not properly compensated [87]. Besides β_2, higher even-order dispersions can also influence MI [88], as well as odd-order dispersions if wavelength-dependent loss is present [89]. Finally, although SPM-induced MI occurs in the anomalous dispersion regime, MI can also be induced by XPM between two copropagating beams in the normal dispersion regime (see XPM below).

The above discussion of MI was restricted to the scalar case. However, a modified type of MI can occur, called vectorial or polarization MI (PMI), when the CW beam excites both polarization components simultaneously [90], [91]. Like MI, PMI is due to the exponential growth of a periodic perturbation and manifests itself by the breakup of the CW beam into a train of very short pulses. In PMI, however, the coupling between the two polarization components of the beam plays the essential role. PMI can, in fact, be described as the result of XPM between these two components in the presence of a periodic perturbation on the amplitude of the CW beam. Because it involves XPM between two polarization components, PMI can occur in both the anomalous and the normal dispersion regime. Several different behaviors can then be observed, depending on the intrinsic modal dispersion of the fiber and on the nature and degree of birefringence. One must consider three separate cases. i) In highly birefringent fibers, the coherence between the two polarization components can be neglected and PMI depends simply on the CW beam power and on the birefringence of the fiber [92]. At lower power, the gain curve is narrow and its maximum occurs at a higher frequency $\Omega_{\max}$, while at higher power, the gain curve is broader, and its maximum occurs at a lower frequency. $\Omega_{\max}$ can also be tuned by modifying the birefringence of the fiber. PCFs provide a particularly interesting example of the effect of birefringence on PMI. 3.9-THz sidebands were recently reported in an elliptical core

PCF with a 7% eccentricity [93]. ii) In weakly birefringent fibers, the coherence between the two polarization components must be taken into account. This adds an FWM term in the nonlinear polarization [see b) below (12)] and leads to a more complex PMI spectrum. Different behaviors are then observed when the CW beam is polarized parallel to the slow or parallel to the fast axis. In the former case, the nonlinear birefringence adds to the intrinsic linear birefringence. In the latter case, it reduces it and a particular instability can develop for optical powers such that the nonlinear birefringence exactly cancels the intrinsic linear birefringence. In that case, the derivative of the polarization beat length with respect to power $\mathrm{d}L_{\mathrm{B}}/\mathrm{d}P$ becomes infinite, and large fluctuations in the output polarization can be induced by small power fluctuations (polarization instability). iii) Isotropic fibers represent a third case, with zero birefringence. Although this case is not strictly realizable, fibers that are spun during drawing do indeed exhibit very little intrinsic birefringence [94], [95]. Nonetheless, they can still exhibit PMI, albeit independent of the polarization of the incident beam, as expected in an isotropic medium. New applications also become possible, such as the generation of polarization-domain walls [96].

Finally, a number of recent studies have investigated fibers with more complex dispersion characteristics. For instance, a higher MI gain and a greater stability of the pulses generated through it have been shown in dispersion-decreasing fibers [86]. MI has also been investigated in dispersion-flattened fibers [97], in which higher order dispersions must be included, and in fibers with periodic and random dispersion [98]. In the case of periodic dispersion (as in dispersion-managed fibers), new sidebands appear and the MI gain bandwidth decreases. Conversely, random dispersion reduces the overall MI gain.

2) Cross-Phase Modulation (XPM): XPM is a similar effect to SPM, but it involves two optical beams instead of one [99]. In XPM, the intensity modulation of one of the beams results in a phase modulation of the other. As in SPM, the phase modulation translates into a frequency modulation that broadens the spectrum. However, because the total intensity is the square of a sum of two electric-field amplitudes, the spectral broadening caused by XPM is twice as large as in SPM

$$\begin{aligned} n = n_0 + n_2|E_1 + E_2|^2 &\Rightarrow \phi_{\mathrm{NL}}^{\omega_1}(z) \\ &= \frac{2\pi n_2}{\lambda A_{\mathrm{eff}}}\left[|E_1|^2 + 2|E_2|^2\right]. \end{aligned} \tag{15}$$

In the expression for the nonlinear phase shift above, the presence of two terms shows that XPM (second term) is always accompanied by SPM (first term) [see also (12)]. A similar expression can be written for the second beam, $\phi_{\mathrm{NL}}^{\omega_2}(z)$. If one of the two beams (the pump) is much stronger than the other (the probe or signal), XPM will primarily act from that pump beam to the weaker signal beam. It should also be obvious that XPM requires that the two beams overlap in time and in space. In the case of pulses, this means that they should have similar GVDs, so that the two modes do not walk off each other.

As for SPM, XPM introduces a nonlinear phase shift which, according to (13), translates into spectral broadening. XPM can also result in the development of a multipeak temporal structure of the pulses or optical wavebreaking. This is due to the combined effect of the XPM-induced chirp and the GVD. For normal dispersion, the wavebreaking will appear on the leading edge of the signal pulse if the latter interacts with the trailing edge of the pump pulse and on the trailing edge of the signal pulse if it interacts with the leading edge of the pump pulse. This is due to the different sign of the XPM-induced chirp in the two cases, combined with the different propagation velocities of the different parts of the signal pulse induced by the GVD. In one case, the peak of the signal pulse will travel faster than its leading edge, and in the other case, the trailing edge of the signal pulse will travel faster than its peak, causing intrapulse interference and a multipeak structure. Also, similar to the SPM case, a periodic perturbation can lead to an instability (XPM-induced MI) and to the breakup of the CW beams into trains of very short pulses [100].

Compared to SPM, however, the XPM interaction of two beams results in significant differences in the effects observed. First, XPM can occur when either one or both beams are in the normal as well as in the anomalous regime, although the stability range will be different for the two cases since the nonlinear dispersion can be either compensated or magnified by the intrinsic dispersions of the beams. A particular behavior can therefore be selected by designing the dispersion of the fiber appropriately. Second, the nonlinear phase shift and its relative weight with respect to the intrinsic dispersion can change as the two beams with their different GVDs propagate along the fiber.

Because it is a nonlinear effect resulting from a two-beam interaction, XPM can be used for a number of all-optical applications in communication networks: wavelength conversion, [101] demultiplexing [102], [103], switching [104], and other optical-control applications. Being a very fast process, XPM is particularly attractive for wavelength conversion and can, in principle, scale to very-high bit rates and convert multiple wavelengths simultaneously with little or no degradation of the signal. There are, however, some limitations, especially at high bit rates, due to the dispersive walk-off that results from the power-dependent nonlinear dispersion [105]. Because XPM always occurs jointly with SPM, it can also be used for simultaneous demultiplexing and regeneration [106]. XPM can be used advantageously for control applications because, although it does not cause energy to be exchanged between optical beams, it can significantly alter the pulse shape and timing. In particular, one can use a "shepherd" pulse at a separate wavelength from the signal to manipulate and control the signal pulses [107]. XPM has also been used to generate a comb of frequencies centered at an arbitrary wavelength by interacting a femtosecond pulse train with a CW beam [108]. On the reverse side, XPM can create significant problems in WDM communication networks because of the crosstalk it can induce between nearby channels [109]. This can affect the pulse shapes and amplitudes in different channels and lead to the time-dependent depolarization of nearby channels [110]. One solution to mitigate this problem is to introduce a limited amount of dispersion in the system, sometimes by alternating the sign of the dispersion in successive fiber spans, keeping a small but finite residual dispersion (dispersion-managed fiber).

When taking polarization into consideration, an array of new nonlinear effects can be predicted and are indeed observed in fibers. As should be expected, these effects depend intimately on the particular birefringence characteristics of the fiber and on the SOP of the optical wave(s). This birefringence can be intrinsic to the fiber, but it can also be induced by optical nonlinearities. The nonlinear contributions to birefringence are given by [111]

$$\Delta n_x = n_2\left(|E_x|^2 + \frac{2}{3}|E_y|^2\right) \text{ and}$$
$$\Delta n_y = n_2\left(|E_y|^2 + \frac{2}{3}|E_x|^2\right) \quad (16)$$

where n_2 is the nonlinear parameter defined earlier. From (16), it is easy to see that the nonlinear birefringence and related effects must depend on the relative optical intensities in the x and y direction. These two components interact nonlinearly in a way that is analogous to XPM, resulting in a relative nonlinear phase shift between the two components [112]:

$$\Delta\phi_{\mathrm{NL}} = \gamma L_{\mathrm{eff}}(1-B)(P_x - P_y) \quad (17)$$

in which $P_{x,y}$ are the powers in the x and y components, respectively, and B describes the ellipticity of the fiber ($B = 2/3$ for a linearly birefringent fiber). Such a relative nonlinear phase shift can be introduced by copropagating a strong pump, polarized along the x-axis of the fiber, along with a weak arbitrarily polarized signal. $\Delta\phi_{\mathrm{NL}}$ then determines the particular evolution of the polarization as the beam propagates and can, for instance, lead to a rotation of the polarization (optical Kerr effect) [113], [114]. When taking the respective polarization of the two beams into account, XPM can also give rise to interesting temporal and spectral polarization effects. In a pump-probe situation, the probe polarization can be shown to rotate, with different parts of the pulse developing different SOP [114].

3) Solitons: Under the combined influence of SPM or XPM and dispersion, short pulses can evolve towards a solitonic state, in which they retain their shape as they propagate, and can travel undistorted over long distances [115]. Solitons occur when the nonlinear dispersion is exactly compensated by the intrinsic chromatic dispersion across the entire pulse [75], [116].This condition is satisfied for pulses whose normalized shape can be described by the following sech function [117]

$$u(\xi,\tau) = \eta \sec\mathrm{h}(\eta\tau)\exp\left(\frac{i\eta^2\xi}{2}\right) \quad (18)$$

in which the parameter η designates the soliton amplitude, $\tau = t/t_0$ is the time t normalized by the width of the incident pulse t_0, and $\xi = z/L_{\mathrm{D}}$ is the distance traveled normalized by the dispersion length L_{D}. A fundamental characteristic of solitons is the relationship that exists between its width and its amplitude. In real units, the soliton width changes with η as t_0/η, i.e., it is inversely proportional to its amplitude.

Although the necessary condition for the existence of solitons might seem improbable, in practice, very short pulses can spontaneously evolve towards a solitonic state. For example, the ultrashort pulses generated through MI can evolve into solitons by shedding energy at their edges where SPM is not as strong as in the central part of the pulse. Alternatively, sufficiently narrow and energetic pulses directly launched into a fiber can also evolve into solitons in the same manner. If solitons can form relatively easily, they can nevertheless be annihilated by perturbations, such as loss or noise. By reducing the amplitude of the solitonic pulse and, therefore, also that of the SPM- or XPM-induced nonlinear dispersion, loss in a fiber can weaken and even destroy a soliton. However, the effect of loss on a soliton can be compensated by an appropriate dispersion profile along the fiber. Dispersion-decreasing fibers, for example, have been shown to provide greater stability for fundamental solitons [118]. Random variations in the intrinsic dispersion of a fiber can also lead to instability of solitons. This instability can be overcome by periodically alternating the dispersion of the fiber so that the average GVD is low, while the local GVD remains relatively large and can compensate for the nonlinear dispersion. These dispersion-managed solitons, as they are called, are not exactly similar to the solitons described earlier. Although they are stable and can propagate over long distances, their amplitude and width oscillate in a periodic manner, they are chirped, and their shape is closer to a Gaussian than to a hyperbolic secant form [119].

Solitons are now being used in long-haul optical-communication systems, and a number of recent and not-so-recent review papers have covered the subject well [120]–[124]. Dispersion-managed solitons for optical-fiber communications are reviewed in [125] and [126]. Finally, it should be clear from (18) that the solitons discussed above are temporal solitons. Over the past few years, however, another type of soliton has been extensively studied, the spatial soliton [127]. There also exists many review articles on this subject and the interested reader is referred to these [128], [129]. A particularly interesting aspect, and one of relevance for optical communications, is the interaction between spatial solitons and its control [130].

4) Parametric Processes—FWM: The interaction of two or more lightwaves can lead to a second kind of $\chi^{(3)}$ nonlinearities. These involve an energy transfer between waves and not simply a modulation of the index seen by one of them due to the other. This interaction is often referred to as "parametric," and these nonlinearities lead to parametric processes. In addition to sufficiently high powers to induce optical nonlinearities (n_2 or γ), such coherent processes also require that the two light waves be phase-matched, i.e., that their phase velocities be the same [131]. This condition is much more stringent than the one already stated for XPM, in which only the group velocities needed to be similar so that pulses would overlap. The phase-matching condition applies to the sum of the wavevectors of the different waves participating in the process and can be written as [132]

$$\kappa \equiv \Delta k_{\mathrm{M}} + \Delta k_{\mathrm{W}} + \Delta k_{\mathrm{NL}} = 0 \quad (19)$$

in which the material contribution is $\Delta k_{\mathrm{M}} = \sum_i n_i\omega_i/c$, $\Delta k_{\mathrm{W}} = \sum_i \Delta n_i\omega_i/c$, where Δn_i is the waveguide-dispersion contribution to the index experienced by wave i, and $\Delta k_{\mathrm{NL}} = \sum_i \gamma P_i$. The phase-matching condition can be satisfied through changes in the balance between material dispersion, waveguide dispersion and nonlinear dispersion experienced by the different beams. It is important to note that this condition can only be satisfied if one of the three dispersions is negative, as for instance Δk_{M} in the anomalous dispersion regime. Also, for single-mode fibers, $\Delta k_{\mathrm{W}} \ll \Delta k_{\mathrm{M}}$, except near the ZDW λ_{ZDW}. The wavelength range near the ZDW of the fiber is a special one, where the waveguide and nonlinear dispersion can be adjusted to cancel the small material dispersion. The first one can be adjusted through proper fiber design, and the second, by proper choice of the optical powers [133].

$\chi^{(3)}$ parametric processes include FWM, THG, and parametric gain. Second harmonic generation (SHG), which is a $\chi^{(2)}$ process, and therefore not observed because of the optical isotropy of optical fibers, can nevertheless be induced through poling, and can then lead to cascaded $\chi^{(3)}$-like parametric processes. In a $\chi^{(3)}$ parametric process, three waves interact to produce a fourth one. Because this is a coherent interaction (between fields and not just between intensities or powers), both frequencies and wavevectors must be conserved (energy conservation and wavevector conservation or phase matching):

$$\pm\omega_1 \pm \omega_2 \pm \omega_3 = \pm\omega_4 \quad \text{and} \quad \pm k_1 \pm k_2 \pm k_3 = \pm k_4. \tag{20}$$

Clearly, there can be a large variety of such processes, depending on the particular product of the four fields. Because of the low probability of satisfying the phase-matching condition, the mixing of four fields of different frequencies is not very likely in general. Two of the more commonly encountered processes are FWM and THG:

$$-\text{in FWM}: \ \omega_1 + \omega_2 = \omega_3 + \omega_4 \ \text{ and } \ k_1 + k_2 - k_3 - k_4 = 0. \tag{21}$$

A special case is degenerate FWM, in which two high-intensity waves, with respective frequencies $\omega_1 = \omega_2$ and $\omega_3 = \omega_4$, interact. The mixing process then generates two new waves at $(2\omega_1 - \omega_3)$ and $(2\omega_3 - \omega_1)$. If a signal is propagating with the same frequency as one of these two new waves, it will be amplified and a second wave, the idler, will be generated. Partially degenerate FWM can be used for frequency conversion:

$$\omega_1 = \omega_2 \rightarrow 2\omega_1 - \omega_3 = \omega_4 \tag{22}$$

which can also be rewritten as $\omega_1 - \omega_3 = \omega_4 - \omega_1$. Through this partially degenerate FWM, a strong pump generates two waves at ω_3 and ω_4, respectively designated as Stokes and anti-Stokes, by analogy with the SRS or the signal and the idler.

$$-\text{in THG}: \quad \omega_1 = \omega_2 = \omega_3 \rightarrow 3\omega_1 = \omega_4. \tag{23}$$

One of the two most common applications of FWM is wavelength conversion or wavelength exchange [134]. The conventional way of performing wavelength conversion is through phase conjugation of the signal to the idler according to (22), with ω_1 being the frequency of the pump, ω_3 the frequency of the signal, and ω_4 the idler frequency. Due to phase matching, ω_3 and ω_4 are symmetric with respect to the ZDW [135]. A scheme for tunable wavelength conversion has also been demonstrated over a wide spectral range through (asymmetric) FWM by choosing two pumps at frequencies ω_1 and ω_2, with the signal at frequency ω_3 generating the idler at ω_4 [134]. In this scheme, the signal and idler wavelengths do not need to be symmetric with respect to λ_{ZDW} and can, therefore, be chosen at will over a wide interval.

The other major application of FWM is parametric amplification, which is the basis for optical parametric amplifiers and lasers. Parametric amplification, in its simplest form, results from the degenerate FWM process described above, in which a strong pump at ω_1 is launched in the fiber along with a weak signal at ω_3, resulting in the amplification of the latter and the generation of the idler at frequency ω_4. The gain g is then given by [136]

$$g^2 = \left[(\gamma P_1)^2 - \left(\frac{\kappa}{2}\right)^2\right] \tag{24}$$

where γ is the nonlinear coefficient (9), κ, the phase mismatch introduced earlier (19), and P_1 is the pump power. As indicated above, $\kappa = 0$ for perfect phase matching. Parametric amplification has also been demonstrated using a modulation interaction between two spectrally distant CW pumps. The proposed scheme provides flat gain over a bandwidth in excess of 22 nm [137]. It is worth noting that, because of the generation of an idler, both the amplification of the signal and wavelength conversion can be done simultaneously with FWM [136]. Other dual-purpose applications are parametric amplification and demultiplexing in WDM systems, when the signal is composed of multiwavelengths [138]. The desired wavelength can then be isolated through filtering. An excellent review of fiber-based optical parametric amplifiers and their applications was recently published by Hansryd *et al.* [139].

FWM has also been applied to the optical regeneration or reshaping of pulses [140]. Injecting a signal and a strong CW pump into a DSF results in several wavelength-converted replicas of the signal, with a step-index transfer function for higher order mixing products. A similar effect can be used to expand a modulated CW lightwave into a comb of discrete and equally spaced frequencies [141]. A novel FWM-based dispersion-monitoring method has also been demonstrated with a 40-Gb/s signal [142]. The signal pulse stream, used as a parametric pump, is mixed with a weak CW lightwave at a different wavelength. The power of the idler generated is shown to depend on the pulsewidth, and therefore on the accumulated dispersion.

Due to the phase-matching condition, dispersion plays an even bigger role in FWM than in other nonlinear processes. In conventional fibers, dispersion fluctuations can translate into λ_{ZDW} fluctuations and reduce FWM efficiency [143]. If needed, FWM can also be suppressed in a more controlled manner by using dispersion-decreasing fibers [144], which can advantageously relax the power limitations in WDM systems. Polarization mode dispersion (PMD) constitutes another source of dispersion, which can lead to fluctuations in $\lambda_{\rm ZDW}$ and, as a result, to fluctuations in idler power [145]. A general vector theory of polarization effects on FWM and parametric amplification is presented in [146]. In fiber transmission systems, polarization can also be used to limit intrachannel nonlinear effects. One method that has been proposed is to use orthogonal SOP for adjacent bits [147]. Birefringence and its variations along the fiber add yet another dimension to polarization effects in FWM. The case of random birefringence is particularly relevant to optical communications, since most single-mode fibers used are weakly birefringent [148]. Finally, parametric processes, in general, and FWM in particular, make a special contribution to the nonlinear generation of a supercontinuum of frequencies, an effect that has primarily been observed in new PCFs (see below).

III. Highly Nonlinear Fibers (HLNFs)

In order to take advantage of the nonlinearities described above and to further enhance them, novel optical fibers have been designed and fabricated [149]. According to the previous equations, the parameters that determine the strength of these nonlinearities are the effective area $A_{\rm eff}$, the effective length $L_{\rm eff}$, and the nonlinear coefficient γ. Clearly, these nonlinearities become important when the effective length $L_{\rm eff}$ exceeds the relevant nonlinear length, $L_{\rm G}$ or $L_{\rm NL}$, as given at the beginning of this paper. Another essential characteristic for the development of distributed optical nonlinearities in fibers is the chromatic dispersion, which can be characterized by the dispersion length $L_{\rm D}$. The shorter the $L_{\rm D}$, the more important the role dispersion plays. We first describe the novel HNLFs with respect to the major fiber parameters introduced earlier and then discuss fibers with new dispersion and birefringence characteristics.

HNLFs can be obtained by reducing the effective core area $A_{\rm eff}$ and increasing the index contrast $\Delta n \equiv n_{\rm core} - n_{\rm clad}$, in order to confine the mode more tightly in the core, or by increasing the gain coefficient g. The reduction of $A_{\rm eff}$ can be achieved by an appropriate design of the index profile, both in terms of its width and contrast. Reducing the size of the doped region increases the optical power density in the core. Simultaneously, increasing the doping level increases the index contrast between the core and the undoped cladding region, thus pulling the mode further inward to the center of the core region. Novel silica fibers have been designed and fabricated, in which the core size has been reduced, as well as more heavily doped [150]. With a 2-μm core radius and an increased Ge-doping, a ninefold increase in fiber nonlinearity has been achieved, compared with conventional silica DSFs [151]. Such fibers can exhibit nonlinear coefficients γ of $\sim 20\ {\rm W}^{-1}{\rm km}^{-1}$ and low attenuation of 0.5 dB/km and have been shown to exhibit greater FWM conversion efficiency [152]. Pb-doped silica fibers have been fabricated with much higher nonlinear coefficients $\gamma \sim 640\ {\rm W}^{-1}{\rm km}^{-1}$ but with a high loss of 2.6 dB/m [153]. Bi_2O_3-doped silica fibers with a step-index structure and a very small effective area $A_{\rm eff} = 5\ \mu{\rm m}^2$ have been shown to have $\gamma > 600\ {\rm W}^{-1}{\rm km}^{-1}$ [154], [155].

An advantage in changing the index profile is the possibility to shift the ZDW from 1310 nm to the most common operating wavelength of 1550 nm, and thus enhance optical nonlinearities at that wavelength. This can be achieved with a high Ge-doping level in the core and fluorine doping of the cladding, which, in addition to shifting $\lambda_{\rm ZDW}$ to 1550 nm, also increases the index contrast and therefore the confinement [156]. The resulting higher nonlinearities have recently been exploited for a broadband dynamic dispersion-compensation fiber device based on SPM. In this device, dynamic compensation of up to 240 ps/nm has been demonstrated with a 40-Gb/s signal [157]. Conversely, high-performance dispersion-compensating fibers have been fabricated in which the nonlinear effects have been suppressed, particularly SPM [158]. In designing fibers with particular dispersion characteristics, PCFs offer the greatest versatility yet. These are fibers in which the cladding is composed of air holes running the length of the fiber parallel to the core. They are discussed in the next section.

From the above, it is clear that the addition of appropriate dopants in silica can significantly increase the gain coefficient g. Fibers made of glasses other than silica also show much promise for nonlinear applications. The most investigated are tellurites, mixed with Na and Zn [159]–[161] or Zn and Nb [162], Zn and W [163], chalcohalides, e.g., GeS_2-based with $n_2 \sim 7.5 \times 10^{-15}\ {\rm cm}^2/{\rm W}$ [164], and chalcogenides [165], e.g., As_2Se_3 [166] and As_2S_3 with $n_2 \sim 1$ to $4 \times 10^{-14}\ {\rm cm}^2/{\rm W}$ [167], [168]. Almost two orders of magnitude higher than pure silica. In As_2S_3, ultrafast switching of pulse trains at 80-GHz repetition rates has been demonstrated with low timing jitter [169].

If optical fibers only exhibit third-order or $\chi^{(3)}$ nonlinearities, it is important to note that second-order or $\chi^{(2)}$ nonlinearities can be electrically induced [170], [171] or photoinduced [172]–[174]. This is particularly true of those fibers made of glasses containing polar radicals [175]. When exposed to subbandgap light, these fibers become birefringent and exhibit $\chi^{(2)}$ nonlinearities [176]. Similar photoinduced effects can be obtained in silica fibers after X-ray or neutron irradiation.

Photonic Crystal Fibers (PCFs): The most exciting development in fibers and fiber nonlinearities is undoubtedly the invention of the microstructured fibers [PCF and photonic bandgap fibers (PBGF)] [177], [178]. These have added an entirely new dimension to fiber design and are creating many new opportunities for nonlinear optical effects and applications [179]. PCFs are index guiding, i.e., they guide light through total internal reflection (TIR). However, because of the holey cladding, their guiding and modal properties are significantly different from those of conventional fibers [180]. First, because the effective refractive index of the holey cladding decreases with decreasing wavelength, PCFs can be made single mode at all wavelengths [181]. This is easily seen from the expression for the V number

$$V \equiv \frac{2\pi}{\lambda} a \left(n_{\rm core}^2 - n_{\rm cladding}^2\right)^{\frac{1}{2}} \tag{25}$$

in which λ is the free-space wavelength, a is the core radius, and $n_{\rm cladding}$ is an effective index that depends on the particular geometry of the cladding (hole size d and separation or pitch Λ).

In practice, PCFs with $d/\Lambda \leq 0.45$ are single mode at all wavelengths [182]. For values greater than 0.45, PCFs still behave as single-mode fibers for wavelengths that are longer than a certain cutoff wavelength. Second, because of the large index contrast between the solid core and holey cladding, the effective area A_{eff} can be made very small and the light more tightly confined within the solid core. A numerical method for the calculation of A_{eff} and results are given in [183]. At 1.55 μm and for $d/\Lambda = 0.45$ with $\Lambda = 3$ μm, A_{eff} is found to be approximately 13 μm^2. This can be compared with the effective area of SMF28, $A_{\mathrm{eff}} \approx 80$ μm^2. Consequently, PCFs are characterized by a greater critical angle θ_{c} and a much greater numerical aperture NA [184]:

$$\mathrm{NA} = \sin\theta_{\mathrm{c}} \approx \left(1 + \frac{\pi A_{\mathrm{eff}}}{\lambda^2}\right)^{-\frac{1}{2}}. \tag{26}$$

Using the above values, NA $\sim$ 0.24 for PCF, compared to $\sim$ 0.08 for conventional fibers. This can obviously be an issue when coupling PCFs to conventional fibers, and it is often convenient to use a short length of an intermediate NA conventional fiber to splice to the PCFs in the splicing operation. Although a small-core PCF offers tight mode confinement, it can also be accompanied by significantly higher confinement losses, which are damaging for applications [185]. Proper design can minimize these losses and yield optical nonlinearities in PCF more than 50 times higher than in conventional fibers. Also, with these higher nonlinearities, shorter lengths of fibers are needed and the loss becomes less of an issue.

In addition to these special modal properties, PCFs also possess very special dispersion properties, which depend on the particular geometry of the fiber, hole diameter d, and pitch Λ. In particular, they often exhibit an inverted bell-shaped dispersion curve, with two ZDWs. For example, an ultraflat dispersion of less than 1 ps/nm/km was recently reported between 1.1 μm and ~ 1.8 μm for a PCF with $d/\Lambda = 0.22$, and $\Lambda = 2.59$ μm, giving NA $\sim$ 0.23 at 1.5 μm and $A_{\mathrm{eff}} \approx 13$ μm^2 [186].

The special properties of PCFs (tight confinement of the light and tunable dispersion) make them particularly suitable for the observation of nonlinear effects [187]–[189]. One of the most spectacular and now commonly reported effects is the generation of a continuum of wavelengths by a pulsed monochromatic beam propagating in the fiber, also called SCG [190], [191]. A number of studies, both experimental and theoretical, have been devoted to the mechanism of this generation. Interestingly, it appears that this mechanism depends on the duration of the initial pulse. For pulses in the femtosecond range (100–200 fs), the supercontinuum is initially generated through the formation of a Raman soliton, followed by the emission of blue-shifted nonsolitonic components (soliton fission) [192], [193]. For pulses in the picosecond range (10–100 ps), SCG results from SRS for the generation of the longer wavelengths, followed by FWM for the generation of the shorter ones [194]. However, it is important to stress that the shape and width of the generated spectrum are also very sensitive to the initial pulse energy [195]. This may explain why there still appears to be some controversy concerning the exact spectral-broadening mechanism at work in specific cases, solitonic or parametric. Recent time-resolved studies of SCG should provide additional information and help resolve this controversy [196], [197].

Because some of the processes involved in SCG require phase matching, it is also sensitive to the dispersion characteristics of the fiber. Accordingly, in PCFs that are designed to have two ZDWs with a very low dispersion between them, SCG is found to be independent of the details of the input pulse over a wide range of input pulse parameters [198]. One can also design the fiber specially, so that it is phase-matched in a certain wavelength range. When applied to the case of SCG, the dispersion of the fiber can be engineered so as to enhance the transfer of energy from the monochromatic pump beam preferentially to a particular wavelength range [199]. In another report, nondegenerate FWM and 13-dB parametric gain was reported in a 6.1-m long fiber with a pump power of only 6 W [200]. SCG has also been studied in birefringent PCFs and a mechanism proposed [201], which agrees with the mechanisms described earlier. Numerical calculations predict that the pulse-to-pulse polarization state of SCG may fluctuate because of vector (or polarization) MI [202]. MI sidebands at 3.9 THz have also been observed in a birefringent PCF with an eccentricity of 7% [93]. The number one advantage of PCFs is the design flexibility they offer. This is well illustrated in numerical calculations for a triangular PCF that predict a significantly improved Raman-gain performance [203].

Finally, although most of the PCFs fabricated and studied to date have been made of silica, PCFs have also been fabricated and studied with other glasses. A multimode PC tellurite fiber with a minimum loss of 2.3 dB/m has recently been reported to exhibit strong SRS [204]. A highly nonlinear Bi_2O_3-based glass holey fiber has also been measured to have a nonlinear coefficient γ of 460 W^{-1}km^{-1} at 1550 nm [205]. A multimode tellurite PCF has been fabricated with $A_{\mathrm{eff}} = 21$ μm^2, exhibiting a loss of 2.3 dB/m, but still strong SRS with subnanosecond pulses [206].

While there remain serious practical issues to be addressed before PCFs can find their way into optical communication networks, a number of applications have already been demonstrated [207], [208]. For instance, an FWM-based 10-Gb/s tunable wavelength converter has been fabricated in a 15-m long PCF with a γ of 70 W^{-1}km^{-1} and an SBS threshold of 21 dBm. A retiming and reamplification (2R) regenerative all-optical switch has been reported, based on 3.3 m of a PCF with $A_{\mathrm{eff}} \approx 2.8$ μm^2 [209]. A 36-channel 10-GHz pulse source has been realized in a normally dispersive holey fiber by slicing a supercontinuum spectrum through an arrayed-waveguide grating [210]. Raman amplification has been achieved in a 75-m section of the same fiber, with a gain of 42 dB and a noise figure of 6 dB, and ultrafast Raman-induced signal modulation with an 11-dB signal extinction ratio. At lower pump powers, it is also possible to generate a simple Raman continuum of wavelengths, which can serve as a broadband source. Such a source has been demonstrated to be 324-nm wide and with a spectral power density greater than 10 mW/nm [211].

The other type of microstructured fiber is the hollow core fiber or PBGF, in which light is guided through a bandgap mechanism. Although these fibers are not intrinsically nonlinear, they can be loaded with gases that can themselves exhibit nonlinear effects. SRS has thus been reported in a hydrogen-loaded PBGF [212] and self-induced transparency has been predicted theoretically in a hollow-core fiber containing resonant two-level atoms [213].

IV. Conclusion

Optical nonlinearities in fibers give rise to a wealth of new effects. This is primarily due to the fact that, because these nonlinearities operate in a distributed manner, the effects they produce vary widely with the chromatic dispersion and birefringence characteristics of the fiber and, by consequence, with the wavelength, chirp, and polarization of the propagating lightwaves. In addition, several nonlinearities may act simultaneously, as in the examples of self-phase modulation (SPM) and cross-phase modulation (XPM), XPM and four-wave mixing (FWM), or stimulated Raman scattering (SRS) and FWM, resulting in an even greater variety of manifestations; supercontinuum generation (SCG) and soliton formation are two typical examples of combined nonlinearities. Nonlinear effects can be detrimental for optical communications, especially in wavelength-division multiplexing (WDM) systems, where they can result in backscattering [stimulated Brillouin scattering (SBS)], noise (spontaneous Raman), pulse distortion (SPM, XPM, MI), and crosstalk between channels (XPM, FWM). Conversely, they are extremely useful for a variety of applications, from fiber lasers and amplifiers to wavelength converters, demultiplexers, optical switches, etc. Nonlinear effects will be particularly important in the next generation of optical networks, which will rely on all-optical functions for higher speed and greater capacity. All-optical functions should allow the partial elimination of optical-electronic-optical (O-E-O) conversion in optical networks, making them more transparent and more easily reconfigurable. The main challenge in all-optical networks will be controlling these nonlinearities and, in particular, their interplay. This will certainly require new types of fibers. For example, new glass compositions may provide intrinsically flatter SRS gain over a wider range of wavelengths, and new fiber designs, dispersion maps, and birefringence characteristics that can be precisely tuned to properly balance the desired nonlinearities. In this regard, photonic crystal fibers (PCFs) hold great promise.

References

[1] L. G. L. Wegener, M. L. Povinelli, A. G. Green, P. P. Mitra, J. B. Stark, and P. B. Littlewood, "The effect of propagating nonlinearities on the information capacity of WDM optical fiber systems: Cross-phase modulation and four-wave mixing," *Physica, D*, vol. 189, no. 1–2, pp. 81–99, Feb. 15, 2004.

[2] M. Wu and W. I. Way, "Fiber nonlinearity limitations in ultra-dense WDM systems," *J. Lightw. Technol.*, vol. 22, no. 6, pp. 1483–1498, Jun. 2004.

[3] A. R. Chraplyvy, "Limitations on lightwave communications imposed by fiber optic nonlinearities," *J. Lightw. Technol.*, vol. 8, no. 10, p. 1548, Oct. 1990.

[4] B. B. Tiwari, V. Prakash, V. Tripathi, and N. Malaviya, "Nonlinear effects in optical fiber transmission system," *IETE Tech. Rev.*, vol. 16, no. 5–6, pp. 461–479, Sep.–Dec. 1999.

[5] E.-H. Lee, K. H. Kim, and H. K. Lee, "Nonlinear effects in optical fiber: Advantages and disadvantages for high capacity all-optical communication application," *Opt. Quantum Electron.*, vol. 34, no. 12, pp. 1167–1174, Dec. 2002.

[6] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. San Diego, CA: Academic, 1995, p. 20.

[7] ——, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001.

[8] E. P. Ippen, *Laser Applications to Optics and Spectroscopy*, vol. 2, S. F. Jacobs, J. F. Scott, and M. O. Scully, Eds. Reading, MA: Addison-Wesley, 1975, ch. 6.

[9] R. Boyd, *NonLinear Optics*. San Diego, CA: Academic, 1992.

[10] R. W. Hellwarth, J. Cherlow, and T. T. Yang, "Origin and frequency dependence of nonlinear optical susceptibilities of glasses," *Phys. Rev. B*, vol. 11, no. 2, p. 964, Jan. 1975.

[11] R. W. Hellwarth, "Third-order optical susceptibilities of liquids and solids," *Prog. Quantum Electron.*, vol. 5, no. 1-A, pp. 1–68, 1977.

[12] Y. R. Shen, *Principles of Nonlinear Optics*. New York: Wiley, 1984.

[13] D. Marcuse, "Pulse distortion in single-mode fibers," *Appl. Opt.*, vol. 19, no. 10, pp. 1653–1660, May 15, 1980.

[14] R. H. Stolen and E. P. Ippen, "Raman gain in glass optical waveguides," *Appl. Phys. Lett.*, vol. 22, no. 6, p. 276, Mar. 1973.

[15] K. Vilhelmsson, "Simultaneous forward and backward Raman scattering in low-attenuation single-mode fibers," *J. Lightw. Technol.*, vol. LT-4, no. 4, pp. 400–404, Apr. 1986.

[16] R. G. Smith, "Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering," *Appl. Opt.*, vol. 11, no. 11, p. 2489, Nov. 1972.

[17] R. Shuker and R. W. Gammon, "Raman selection rule breaking and the density of states in amorphous materials," *Phys. Rev. Lett.*, vol. 25, no. 4, p. 222, Jul. 1970.

[18] E. P. Ippen and R. H. Stolen, "Stimulated Brillouin scattering in optical fibers," *Appl. Phys. Lett.*, vol. 21, no. 11, p. 539, Dec. 1972.

[19] M. J. Li, S. Li, D. Nolan, U. G. Achmetshin, M. M. Bubnov, A. N. Guryanov, E. M. Dianov, V. F. Khopin, and A. A. Sysoliatin, "New dispersion-decreasing fiber with high SBS threshold for nonlinear signal processing," in *Proc. Optical Fiber Communication Conf. (OFC)*, Anaheim, CA, 2005, pp. 155–157.

[20] K. Shiraki, M. Ohashi, and M. Tateda, "Performance of strain-free SBS suppression fiber," *J. Lightw. Technol.*, vol. 14, no. 4, p. 549, Apr. 1996.

[21] R. K. Pattnaik, S. Texier, J. Toulouse, E. J. H. Davies, P. S. J. Russell, and B. J. Mangan, "Characteristic features of stimulated Brillouin scattering in a holey fiber," in *Proc. Conf. Lasers and Electro-Optics (CLEO); Postconf. Dig.*, Baltimore, MD, vol. 88, *OSA Trends in Optics and Photonics Series*, 2003, pp. 1259–1260.

[22] A. Yeniay, J.-M. Delavaux, and J. Toulouse, "Spontaneous and stimulated Brillouin scattering gain spectra in optical fibers," *J. Lightw. Technol.*, vol. 20, no. 8, pp. 1425–1432, Aug. 2002.

[23] R. W. Tkach, A. R. Chraplyvy, and R. M. Derosier, "Spontaneous Brillouin scattering for single mode fiber characterization," *Electron. Lett.*, vol. 22, no. 19, pp. 1011–1013, 1986.

[24] I. Bongrand, E. Picholle, and C. Montes, "Coupled longitudinal and transverse stimulated Brillouin scattering in single-mode optical fibers," *Eur. Phys. J., D*, vol. 20, no. 1, pp. 121–127, Jul. 2002.

[25] V. Grimalsky, S. Koshevaya, G. Burlak, and B. Salazar-H, "Dynamic effects of the stimulated Brillouin scattering in fibers due to acoustic diffraction," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 19, no. 4, pp. 689–694, Apr. 2002.

[26] I. Bongrand, C. Montes, E. Picholle, J. Botineau, A. Picozzi, G. Cheval, and D. Bahloul, "Soliton compression in Brillouin fiber lasers," *Opt. Lett.*, vol. 26, no. 19, pp. 1475–1477, Oct. 1, 2001.

[27] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001, p. 375.

[28] G. Grosso and A. Hook, "Generation of short pulses by stimulated Brillouin scattering in optical fibers," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 10, no. 5, pp. 946–951, May 1993.

[29] N. L. Taranenko, L. G. Kazovsky, and Y. N. Taranenko, "Three-wave envelope solitons: Possibility of controlling the speed of light in fiber," *J. Lightw. Technol.*, vol. 12, no. 7, pp. 1101–1111, Jul. 1994.

[30] G. F. Levy, "Analysis of the characteristics of a fiber-optic ring resonator used as a Brillouin active delay line," *J. Lightw. Technol.*, vol. 13, no. 7, pp. 1466–1470, Jul. 1995.

[31] S. Sternklar and E. Granot, "Narrow spectral response of a Brillouin amplifier," *Opt. Lett.*, vol. 28, no. 12, pp. 977–979, Jun. 15, 2003.

[32] S. P. Smith, F. Zarinetchi, and S. Ezekiel, "Narrow-linewidth stimulated Brillouin fiber laser and applications," *Opt. Lett.*, vol. 16, no. 6, pp. 393–395, Mar. 15, 1991.

[33] A. Debut, S. Randoux, and J. Zemmouri, "Experimental and theoretical study of linewidth narrowing in Brillouin fiber ring lasers," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 18, no. 4, pp. 556–567, Apr. 2001.

[34] C. N. Pannell, P. S. J. Russell, and T. P. Newson, "Stimulated Brillouin scattering in optical fibers: The effects of optical amplification," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 10, no. 4, pp. 684–690, Apr. 1993.

[35] G. J. Cowle and D. Y. Stepanov, "Hybrid Brillouin/erbium fiber laser," *Opt. Lett.*, vol. 21, no. 16, pp. 1250–1252, Aug. 15, 1996.

[36] G. J. Cowie, D. Yu, and Y. T. Chieng, "Brillouin/erbium fiber lasers," *J. Lightw. Technol.*, vol. 15, no. 7, pp. 1198–1204, Jul. 1997.

[37] A. Loayssa, D. Benito, and M. J. Garde, "Applications of optical carrier Brillouin processing to microwave photonics," *Opt. Fiber Technol.: Mater., Devices Syst.*, vol. 8, no. 1, pp. 24–42, Jan. 2002.

[38] Y. Wang and R. Baettig, "A microwave optical phase modulation system," *IEEE Photon. Technol. Lett.*, vol. 7, no. 5, pp. 570–572, May 1995.

[39] M. O. van Deventer and A. J. Boot, "Polarization properties of stimulated Brillouin scattering in single-mode fibers," *J. Lightw. Technol.*, vol. 12, no. 4, pp. 585–590, Apr. 1994.

[40] A. Yeniay, "Spontaneous and stimulated Brillouin scattering in single mode silica optical fibers," Doctoral dissertation, Lehigh Univ., Bethlehem, PA, May 2002.

[41] M. Gonzalez-Herraez and L. Thevenaz, "Simultaneous position-resolved mapping of chromatic dispersion and Brillouin shift along single-mode optical fibers," *IEEE Photon. Technol. Lett.*, vol. 15, no. 4, pp. 1128–1130, Apr. 2004.

[42] S. Texier, R. K. Pattnaik, and J. Toulouse, "SBS remote and spatially-resolved monitoring of the state of polarization in optical fibers," presented at the Optical Fiber Communication (OFC), Los Angeles, CA, 2004, Paper CWM3.

[43] R. H. Stolen, E. P. Ippen, and A. R. Tynes, "Raman oscillations in glass optical waveguides," *Appl. Phys. Lett.*, vol. 20, no. 2, p. 62, Jan. 1972.

[44] M. N. Islam, "Raman amplifiers for telecommunications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 3, pp. 548–559, May–Jun. 2002.

[45] D. C. Johnson, K. O. Hill, B. S. Kawasaki, and D. Kato, "Tunable Raman fiber optic laser," *Electron. Lett.*, vol. 13, no. 2, p. 53, Jan. 1977.

[46] M. D. Mermelstein, C. Headley, J. C. Bouteiller, P. Steinvurzel, C. Horn, K. Feder, and B. J. Eggleton, "Configurable three-wavelength Raman fiber laser for Raman amplification and dynamic gain flattening," *IEEE Photon. Technol. Lett.*, vol. 13, no. 12, pp. 1286–1288, Dec. 2001.

[47] V. E. Perlin and H. G. Winful, "On distributed Raman amplification for ultrabroad band long-haul WDM systems," *J. Lightw. Technol.*, vol. 20, no. 3, p. 409, Mar. 2002.

[48] M. D. Mermelstein, K. Brar, and C. Headley, "RIN transfer measurement and modeling in dual-order Raman fiber amplifiers," *J. Lightw. Technol.*, vol. 21, no. 6, pp. 1518–1523, Jun. 2003.

[49] C. R. S. Fludger, V. Handerek, and R. J. Mears, "Pump to signal RIN transfer in Raman fiber amplifiers," *J. Lightw. Technol.*, vol. 19, no. 8, pp. 1140–1148, Aug. 2001.

[50] V. J. Mazurczyk, G. Shaulov, and E. A. Golovchenko, "Accumulation of gain tilt in WDM amplified systems due to Raman crosstalk," *IEEE Photon. Technol. Lett.*, vol. 12, no. 11, pp. 1573–1575, Nov. 2000.

[51] C. M. McIntosh, J. Toulouse, A. G. Grandpierre, D. N. Christodoulides, and J. M. Delavaux, "Stimulated Raman scattering threshold enhancement via optical filtering," in *Conf. NonLinear Guided Waves*, Tampa, FL, 2001, pp. 226–228.

[52] ——, "Optical transmission link incorporating highpass optical filtering," U.S. Patent 6 466 712 B1, Oct. 15, 2002.

[53] V. I. Karpov, E. M. Dianov, V. M. Paramonov *et al.*, "Laser diode-pumped phosphosilicate fiber Raman laser with an output power of 1 W at 1.48 μm," *Opt. Lett.*, vol. 24, no. 13, p. 887, 1999.

[54] E. Desurvire, A. Imamoglu, and H. J. Shaw, "Low-threshold synchronously pumped all-fiber ring Raman laser," *J. Lightw. Technol.*, vol. LT-5, no. 1, pp. 89–96, Jan. 1987.

[55] D. Dahan, A. Bilenca, and G. Eisenstein, "Noise-reduction capabilities of a Raman-mediated wavelength converter," *Opt. Lett.*, vol. 28, no. 8, pp. 634–636, Apr. 2003.

[56] F. Ahmed and N. Kishi, "All-fiber ultra-fast switching using stimulated Raman scattering," *Opt. Rev.*, vol. 10, no. 3, pp. 146–149, May–Jun. 2003.

[57] Y. O. Barmenkov, A. V. Kiryanov, I. Torres Gomez, and A. N. Starodumov, "Raman-effect-based all-fiber optical controlling," *Laser Phys.*, vol. 13, no. 8, pp. 1119–1122, Aug. 2003.

[58] C. Headley, III and G. P. Agrawal, "Unified description of ultrafast stimulated Raman scattering in optical fibers," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 13, no. 10, pp. 2170–2177, Oct. 1996.

[59] E. A. Golovchenko, P. V. Mamyshev, A. N. Pilipetskii, and E. N. Dianov, "Mutual influence of the parametric effects and SRS in optical fibers," *IEEE J. Quantum Electron.*, vol. 26, no. 10, p. 1815, Oct. 1990.

[60] E. M. Dianov, A. Y. Karasik, P. V. Mamyshev, A. M. Prokhorov, V. N. Serkin, M. F. Stelmakh, and A. A. Fornichev, "Stimulated Raman conversion of multisoliton pulses in quartz optical fibers," *JETP Lett.*, vol. 41, no. 6, p. 242, 1985.

[61] F. M. Mitschke and L. F. Mollenauer, "Discovery of the soliton self frequency shift," *Opt. Lett.*, vol. 11, no. 10, p. 659, Oct. 1986.

[62] J. P. Gordon, "Theory of the self frequency shift," *Opt. Lett.*, vol. 11, no. 10, p. 662, Oct. 1986.

[63] P. C. Reeves and J. R. Taylor, "Wavelentgh and duration tunable sub-ps source using adiabatic Raman compression," *Electron. Lett.*, vol. 37, no. 7, p. 417, Mar. 2001.

[64] K. Chan and W. Cao, "Generation of ultrashort fundamental solitons from CW light using cross-phase modulation and Raman amplification in optical fibers," *Opt. Commun.*, vol. 158, no. 1–6, pp. 159–169, Dec. 15, 1998.

[65] G. Millot, P. Tchofo Dinda, E. Seve, and S. Wabnitz, "Modulational instability and stimulated Raman scattering in normally dispersive highly birefringent fibers," *Opt. Fiber Technol.: Mater., Devices Syst.*, vol. 7, no. 3, pp. 170–205, Jul. 2001.

[66] I. Velchev, R. Pattnaik, and J. Toulouse, "Two-beam modulation instability in noninstantaneous nonlinear media," *Phys. Rev. Lett.*, vol. 91, no. 9, pp. 93905/1–93905/4, Aug. 29, 2003.

[67] F. Vanholsbeeck, P. Emplit, and S. Coen, "Complete experimental characterization of the influence of parametric four-wave mixing on stimulated Raman gain," *Opt. Lett.*, vol. 28, no. 20, pp. 1960–1962, Oct. 15, 2003.

[68] E. M. Dianov, "Advances in Raman fibers," *J. Lightw. Technol.*, vol. 20, no. 8, pp. 1457–1462, Aug. 2002.

[69] K. Kikuchi, K. Taira, and N. Sugimoto, "Highly nonlinear bismuth oxide-based glass fibers for all-optical signal processing," in *Optical Fiber Communication Conf. (OFC), PostConf. Tech. Dig., (IEEE Cat. No.02CH37339)*, Anaheim, CA, vol. 1, 2002, pp. 567–568.

[70] R. Stegeman, "Novel high gain broadband glasses," *Opt. Lett.*, vol. 28, no. 13, p. 1126, Jul. 2003.

[71] S. Marjanovic, J. Toulouse, V. S. Johnson, P. W. Wisk, A. R. Kortan, N. Kopylov, and R. G. Ahrens, "Characterization of new erbium-doped tellurite glasses and fibers," in *Proc. Optical Fiber Communication Conf. (OFC), (IEEE Cat. No.04CH37532)*, Los Angeles, CA, vol. 2, 2004, p. 3.

[72] P. A. Thielen, L. B. Shaw, P. C. Pureza, V. Q. Nguyen, J. S. Sanghera, and I. D. Aggarwal, "Small-core As-Se fiber for Raman amplification," *Opt. Lett.*, vol. 28, no. 16, pp. 1406–1408, Aug. 15, 2003.

[73] H. A. Haus, *Waves and Fields in Optoelectronics*. Englewood Cliffs, NJ: Prentice-Hall, 1984, ch. 10.

[74] R. H. Stolen and C. Lin, "Self phase modulation in silica optical fibers," *Phys. Rev., A*, vol. 17, no. 4, p. 1448, 1978.

[75] J. M. Dudley, A. C. Peacock, and G. Millot, "The cancellation of nonlinear and dispersive phase components on the fundamental optical fiber soliton: A pedagogical note," *Opt. Commun.*, vol. 193, no. 1–6, pp. 253–259, Jun. 15, 2001.

[76] B. R. Washburn, J. A. Buck, and S. E. Ralph, "Transform-limited spectral compression due to self-phase modulation in fibers," *Opt. Lett.*, vol. 25, no. 7, pp. 445–447, Apr. 1, 2000.

[77] J. Limpert, T. Gabler, A. Liem, H. Zellmer, and A. Tunnermann, "SPM-induced spectral compression of picosecond pulses in a single-mode Yb-doped fiber amplifier," *Appl. Phys., B*, vol. 74, no. 2, pp. 191–195, Feb. 2002.

[78] S. A. Planas, N. L. Pires Mansur, C. H. Brito Cruz, and H. L. Fragnito, "Spectral narrowing in the propagation of chirped pulses in single-mode fibers," *Opt. Lett.*, vol. 18, no. 9, pp. 699–701, May 1, 1993.

[79] G. Lenz, B. J. Eggleton, and N. Litchinitser, "Pulse compression using fiber gratings as highly dispersive nonlinear elements," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 15, no. 2, pp. 715–721, Feb. 1998.

[80] S. Shen, C.-C. Chang, H. P. Sardesai, V. Binjrajka, and A. M. Weiner, "Effects of self-phase modulation on sub-500 fs pulse transmission over dispersion compensated fiber links," *J. Lightw. Technol.*, vol. 17, no. 3, pp. 452–461, Mar. 1999.

[81] B.-E. Olsson and D. J. Blumenthal, "Pulse restoration by filtering of self-phase modulation broadened optical spectrum," *J. Lightw. Technol.*, vol. 20, no. 7, pp. 1113–1117, Jul. 2002.

[82] M. Schiess, "Comparison of dispersion compensation schemes including fiber nonlinearities," *J. Opt. Commun.*, vol. 16, no. 3, pp. 92–98, Jun. 1995.

[83] M. Matsumoto, "Performance analysis and comparison of optical 3R regenerators utilizing self-phase modulation in fibers," *J. Lightw. Technol.*, vol. 22, no. 6, pp. 1472–1482, Jun. 2004.

[84] W. J. Tomlinson, R. H. Stolen, and A. M. Johnson, "Optical wavebreaking of pulses in nonlinear optical fibers," *Opt. Lett.*, vol. 10, no. 9, p. 457, Sep. 1985.

[85] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. San Diego, CA: Academic, 1995, p. 137.

[86] W. Xu, S. Zhang, W. Chen, A. Luo, and S. Liu, "Modulation instability of femtosecond pulses in dispersion-decreasing fibers," *Opt. Commun.*, vol. 199, no. 5–6, pp. 355–360, Dec. 1, 2001.

[87] R. Hui, M. O'Sullivan, A. Robinson, and M. Taylor, "Modulation instability and its impact in multispan optical amplified IMDD systems: Theory and experiments," *J. Lightw. Technol.*, vol. 15, no. 7, pp. 1071–1082, Jul. 1997.

[88] H. Zhang, S. Wen, W. Han, and J. Wu, "Generic features of modulation instability in optical fibers," in *Proc. SPIE—Int. Soc. Opt. Eng.*, Wuhan, China, vol. 5279, no. 1, 2004, pp. 443–449.

[89] T. Tanemura, Y. Ozeki, and K. Kikuchi, "Modulational instability and parametric amplification induced by loss dispersion in optical fibers," *Phys. Rev. Lett.*, vol. 93, no. 16, pp. 163902-1–163902-4, Oct. 15, 2004.

[90] S. Trillo, S. Wabnitz, R. H. Stolen, G. Assanto, C. T. Seaton, and G. I. Stegeman, "Experimental observation of polarization instability in a birefringent optical fiber," *Appl. Phys. Lett.*, vol. 49, no. 19, p. 1224, Nov. 1986.

[91] H. Winful, "Polarization instability in birefringent nonlinear media: Application to fiber optic devices," *Opt. Lett.*, vol. 11, no. 1, p. 33, Jan. 1986.

[92] A. Tonello, "The role of birefringence in modulation instability fiber ring resonators," *Opt. Quantum Electron.*, vol. 32, no. 11, pp. 1219–1238, Nov. 2000.

[93] G. Millot, A. Sauter, J. M. Dudley, L. Provino, and R. S. Windeler, "Polarization mode dispersion and vectorial modulational instability in air-silica microstructure fiber," *Opt. Lett.*, vol. 27, no. 9, pp. 695–697, May 1, 2002.

[94] R. E. Schuh, X. Shan, and A. S. Siddiqui, "Polarization mode dispersion in spun fibers with different linear birefringence and spinning parameters," *J. Lightw. Technol.*, vol. 16, no. 9, pp. 1583–1588, Sep. 1998.

[95] M. Fuochi, J. R. Hayes, K. Furusawa, W. Belardi, J. C. Baggert, T. M. Monro, and D. J. Richardson, "Polarization mode dispersion reduction in spun large mode area silica holey fibres," *Opt. Express*, vol. 12, no. 9, pp. 1972–1977, May 2004.

[96] P. Kockaert, M. Haelterman, S. Pitois, and G. Millot, "Isotropic polarization modulational instability and domain walls in spun fibers," *Appl. Phys. Lett.*, vol. 75, no. 19, pp. 2873–2875, Nov. 8, 1999.

[97] M. Yu, C. J. McKinstrie, and G. P. Agrawal, "Modulational instabilities in dispersion-flattened fibers," *Phys. Rev., E Stat. Phys. Plasmas Fluids Relat. Interdiscip. Topics*, vol. 52, no. 1, pt. B, pp. 1072–1080, Jul. 1995.

[98] F. K. Abdullaev and J. Garnier, "Modulational instability of electromagnetic waves in birefringent fibers with periodic and random dispersion," *Phys. Rev., E*, vol. 60, no. 1, pp. 1042–1050, Jul. 1999.

[99] M. N. Islam, L. F. Mollenauer, R. H. Stolen, J. R. Simpson, and H. T. Shang, "Cross-phase modulation in optical fibers," *Opt. Lett.*, vol. 12, no. 8, p. 625, Aug. 1987.

[100] A. S. Gouveia-Neto, M. E. Faldon, A. S. B. Sombra, P. G. J. Wigley, and J. R. Taylor, "Sub-ps pulse generation through XPM-induced MI in optical fibers," *Opt. Lett.*, vol. 13, no. 10, p. 901, Oct. 1988.

[101] V. E. Perlin and H. G. Winful, "All-fiber wavelength conversion using cross-phase modulation and Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 14, no. 2, pp. 176–178, Feb. 2002.

[102] B.-E. Olsson and D. J. Blumenthal, "All-optical demultiplexing using fiber cross-phase modulation (XPM) and optical filtering," *IEEE Photon. Technol. Lett.*, vol. 13, no. 8, pp. 875–877, Aug. 2001.

[103] J. Li, B.-E. Olsson, M. Karlsson, and P. A. Andrekson, "OTDM demultiplexer based on XPM-induced wavelength shifting in highly nonlinear fiber," *IEEE Photon. Technol. Lett.*, vol. 15, no. 12, pp. 1770–1772, Dec. 2003.

[104] V. E. Perlin and H. G. Winful, "Nonlinear pulse switching using cross-phase modulation and fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 13, no. 9, pp. 960–962, Sep. 2001.

[105] P. Ohlen, B.-E. Olsson, and D. J. Blumenthal, "Wavelength dependence and power requirements of a wavelength converter based on XPM in a dispersion-shifted optical fiber," *IEEE Photon. Technol. Lett.*, vol. 12, no. 5, pp. 522–524, May 2000.

[106] J. Yu and P. Jeppesen, "Simultaneous all-optical demultiplexing and regeneration based on self-phase and cross-phase modulation in a dispersion shifted fiber," *J. Lightw. Technol.*, vol. 19, no. 7, pp. 941–949, Jul. 2001.

[107] C. Yeh and L. Bergman, "Pulse shepherding in nonlinear fiber optics," *J. Appl. Phys.*, vol. 80, no. 6, pp. 3174–3178, Sep. 15, 1996.

[108] D. J. Jones, D. A. Diddams, M. S. Taubman, S. T. Cundiff, L.-S. Ma, and J. L. Hall, "Frequency comb generation using femtosecond pulses and cross-phase modulation in optical fiber at arbitrary center frequencies," *Opt. Lett.*, vol. 25, no. 5, pp. 308–310, Mar. 1, 2000.

[109] R. Hui, K. R. Demarest, and C. T. Allen, "Cross-phase modulation in multispan WDM optical fiber systems," *J. Lightw. Technol.*, vol. 17, no. 6, pp. 1018–1026, Jun. 1999.

[110] B. C. Collings and L. Boivin, "Nonlinear polarization evolution induced by cross-phase modulation and its impact on transmission systems," *IEEE Photon. Technol. Lett.*, vol. 12, no. 11, pp. 1582–1584, Nov. 2000.

[111] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001, p. 206.

[112] ——, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001, p. 211.

[113] R. H. Stolen and A. Ashkin, "Optical Kerr effect in glass waveguides," *Appl. Phys. Lett.*, vol. 22, no. 6, p. 294, Mar. 1973.

[114] Q. Lin and G. P. Agrawal, "Vector theory of cross-phase modulation: Role of nonlinear polarization rotation," *IEEE J. Quantum Electron.*, vol. 40, no. 7, pp. 958–964, Jul. 2004.

[115] A. Hasegawa and F. Tappert, "Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers," *Appl. Phys. Lett.*, vol. 23, no. 3, p. 142, Aug. 1973.

[116] L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Experimental observation of ps pulse narrowing and solitons in optical fibers," *Phys. Rev. Lett.*, vol. 45, no. 13, p. 1095, Sep. 1980.

[117] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001, p. 150.

[118] D. Gupta, G. Kumar, and K. Thyagarajan, "Nonlinear pulse propagation in dispersion decreasing fibers," *Opt. Commun.*, vol. 237, no. 4–6, pp. 309–317, Jul. 15, 2004.

[119] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001, p. 164.

[120] H. A. Haus and W. S. Wong, "Solitons in optical communications," *Rev. Mod. Phys.*, vol. 68, no. 2, pp. 423–444, Apr. 1996.

[121] L. F. Mollenauer, J. P. Gordon, and P. V. Mamyshev, *Optical Fiber Telecommunications III*, I. P. Kaminow and T. L. Koch, Eds. San Diego, CA: Academic, 1997, ch. 12.

[122] A. Hasegawa, "Optical solitons in fibers for communication systems," *Optics Photonics News*, vol. 13, no. 2, pp. 33–37, Feb. 2002.

[123] ——, "Soliton-based optical communications: An overview," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1161–1172, Nov./Dec. 2000.

[124] M. Nakazawa, H. Kubota, and E. Yamada, "Generation and transmission of optical soliton pulses," *Electron. Commun. Jpn., Part 2, Electron.*, vol. 80, no. 4, pp. 53–66, Apr. 1997.

[125] W. Forysiak, J. H. B. Nijhof, and N. J. Doran, "Dispersion managed solitons: The key to terabit per second optical fiber communication system," *Optics Photonics News*, vol. 11, no. 5, pp. 35–39, May 2000.

[126] A. Hasegawa, Y. Kodama, and A. Maruta, "Recent progress in dispersion-managed soliton transmission technologies," *Opt. Fiber Technol.: Mater., Devices Syst.*, vol. 3, no. 3, pp. 197–213, Jul. 1997.

[127] G. I. Stegeman and M. Segev, "Optical spatial solitons and their interactions: Universality and diversity," *Science*, vol. 286, no. 5444, pp. 1518–1523, Nov. 19, 1999.

[128] G. I. A. Stegeman, D. N. Christodoulides, and M. Segev, "Optical spatial solitons: Historical perspectives," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1419–1427, Nov. 2000.

[129] Y. S. Kivshar and G. I. Stegeman, "Spatial optical solitons guiding light for future technologies," *Optics Photonics News*, vol. 13, no. 2, pp. 59–63, Feb. 2002.

[130] S. Wabnitz, Y. Kodama, and A. B. Aceves, "Control of optical soliton interactions," *Opt. Fiber Technol.: Mater., Devices Syst.*, vol. 1, no. 3, pp. 187–217, Jun. 1995.

[131] R. H. Stolen, J. E. Bjorkholm, and A. Ashkin, "Phase matched three wave mixing in silica fiber optical waveguides," *Appl. Phys. Lett.*, vol. 24, no. 7, p. 308, Apr. 1974.

[132] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001, p. 399.

[133] S. Song, C. T. Allen, K. R. Demarest, and R. Hui, "Intensity-dependent phase-matching effects on four-wave mixing in optical fibers," *J. Lightw. Technol.*, vol. 17, no. 11, pp. 2285–2290, Nov. 1999.

[134] M. E. Marhic, Y. Park, F. S. Yang, and L. G. Kazovsky, "Widely tunable spectrum translation and wavelength exchange by four-wave mixing in optical fibers," *Opt. Lett.*, vol. 21, no. 23, pp. 1906–1908, Dec. 1, 1996.

[135] S. Wabnitz, "Nonlinear enhancement and optimization of phase-conjugation efficiency in optical fibers," *IEEE Photon. Technol. Lett.*, vol. 7, no. 6, pp. 652–654, Jun. 1995.

[136] R. H. Stolen and B. J. Bjorkholm, "Parametric amplification and frequency conversion in optical fibers," *IEEE J. Quantum Electron.*, vol. 18, no. 7, pp. 1062–1072, Jul. 1982.

[137] S. Radic, C. J. McKinstrie, A. R. Chraplyvy, G. Raybon, J. C. Centanni, C. G. Jorgensen, K. Brar, and C. Headley, "Continuous-wave parametric gain synthesis using nondegenerate pump four-wave mixing," *IEEE Photon. Technol. Lett.*, vol. 14, no. 10, pp. 1406–1408, Oct. 2002.

[138] P. O. Hedekvist, M. Karlsson, and P. A. Andrekson, "Fiber four-wave mixing demultiplexing with inherent parametric amplification," *J. Lightw. Technol.*, vol. 15, no. 11, pp. 2051–2058, Nov. 1997.

[139] J. Hansryd, P. A. Andrekson, M. Westlund, J. Li, and P.-O. Hedekvist, "Fiber-based optical parametric amplifiers and their applications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 3, pp. 506–520, May/Jun. 2002.

[140] E. Ciaramella, F. Curti, and S. Trillo, "All-optical signal reshaping by means of four-wave mixing in optical fibers," *IEEE Photon. Technol. Lett.*, vol. 13, no. 2, pp. 142–144, Feb. 2001.

[141] G. A. Sefler and K.-I. Kitayama, "Frequency comb generation by four-wave mixing and the role of fiber dispersion," *J. Lightw. Technol.*, vol. 16, no. 9, pp. 1596–1605, Sep. 1998.

[142] S. Li and D. V. Kuksenkov, "A novel dispersion monitoring technique based on four-wave mixing in optical fiber," *IEEE Photon. Technol. Lett.*, vol. 16, no. 3, pp. 942–944, Mar. 2004.

[143] K. Tsuji, H. Yokota, and A. M. Saruwatari, "Influence of dispersion fluctuations on four-wave mixing efficiency in optical fibers," *Electron. Commun. Jpn., Part 2, Electron.*, vol. 85, no. 8, pp. 16–24, 2002.

[144] K. Nakajima, M. Ohashi, and Y. Miyajima, "Four-wave-mixing suppression effect of dispersion varying fiber," *IEEE Photon. Technol. Lett.*, vol. 10, no. 4, pp. 537–539, Apr. 1998.

[145] G. P. Agrawal and Q. Lin, "Impact of polarization-mode dispersion on measurement of zero-dispersion wavelength through four-wave mixing," *IEEE Photon. Technol. Lett.*, vol. 15, no. 12, pp. 1719–1721, Dec. 2003.

[146] Q. Lin and G. P. Agrawal, "Vector theory of four-wave mixing: Polarization effects in fiber-optic parametric amplifiers," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 21, no. 6, pp. 1216–1224, Jun. 2004.

[147] C. Xie, I. Kang, A. H. Gnauck, L. Moller, L. F. Mollenauer, and A. R. Grant, "Suppression of intrachannel nonlinear effects with alternate-polarization formats," *J. Lightw. Technol.*, vol. 22, no. 3, pp. 806–812, Mar. 2004.

[148] C. J. McKinstrie, H. Kogelnik, R. M. Jopson, S. Radic, and A. V. Kanaev, "Four-wave mixing in fibers with random birefringence," *Opt. Express*, vol. 12, no. 10, pp. 2033–2055, May 17, 2004.

[149] J. Hiroishi, R. Sugizaki, O. Aso, M. Tadakuma, and T. Shibuta, "Development of highly nonlinear fibers for optical signal processing," *Furukawa Rev.*, no. 23, pp. 21–25, Apr. 2003.

[150] A. Wada, S. Okude, T. Sakai, and R. Yamauchi, "GeO_2 concentration dependence of nonlinear refractive index coefficients of silica-based optical fibers," *Electron. Commun. Jpn., Part 1, Commun. (English translation of Denshi Tsushin Gakkai Ronbunshi)*, vol. 79, no. 11, pp. 12–19, Nov. 1996.

[151] M. J. Holmes, D. L. Williams, and R. J. Manning, "Highly nonlinear optical fiber for all optical processing applications," *IEEE Photon. Technol. Lett.*, vol. 7, no. 9, pp. 1045–1047, Sep. 1995.

[152] M. Onishi, T. Okuno, T. Kashiwada, S. Ishikawa, N. Akasaka, and M. Nishimura, "Highly nonlinear dispersion-shifted fibers and their application to broadband wavelength converter," *Opt. Fiber Technol.: Mater., Devices Syst.*, vol. 4, no. 2, pp. 204–214, Apr. 1998.

[153] P. Petropoulos, H. Ebendorff-Heidepriem, V. Finazzi, R. C. Moore, K. Frampton, D. J. Richardson, and T. M. Monro, "Highly nonlinear and anomalously dispersive lead silicate glass holey fibers," *Opt. Express*, vol. 11, no. 26, pp. 3568–3573, 2003.

[154] T. Nagashima, T. Hasegawa, S. Ohara, N. Sugimoto, K. Taira, and K. Kikuchi, "Bi_2O_3-based highly nonlinear fiber with step index structure," in *Proc. SPIE—Int. Society Optical Engineering*, San Jose, CA, 2004, vol. 5350, pp. 50–57.

[155] K. Kikuchi, K. Taira, and N. Sugimoto, "Highly-nonlinear bismuth oxide-based glass fibers for all-optical signal processing," in *Optical Fiber Communication Conf. (OFC), Postconf. Tech. Dig., (IEEE Cat. No.02CH37339)*, Anaheim, CA, vol. 1, 2002, pp. 567–568.

[156] M. Onishi, T. Okuno, T. Kashiwada, S. Ishikawa, N. Akasaka, and M. Nishimura, "Highly nonlinear dispersion-shifted fibers and their application to broadband wavelength converter," *Opt. Fiber Technol.: Mater., Devices Syst.*, vol. 4, no. 2, pp. 204–214, Apr. 1998.

[157] S. Li, M. Sauer, Z. D. Gaeta, D. V. Kuksenkov, S. R. Bickham, G. E. Berkey, M.-J. Li, and D. A. Nolan, "Broad-band dynamic dispersion compensation in nonlinear fiber-based device," *J. Lightw. Technol.*, vol. 22, no. 1, pp. 29–38, Jan. 2004.

[158] M. Onishi, T. Kashiwada, Y. Ishiguro, Y. Koyano, M. Nishimura, and H. Kanamori, "High-performance dispersion-compensating fibers," *Fiber Integr. Opt.*, vol. 16, no. 3, pp. 277–285, 1997.

[159] J. S. Wang, E. M. Vogel, and E. Snitzer, "Tellurite glass: A new candidate for fiber devices," *Opt. Mater.*, vol. 3, no. 3, pp. 187–203, Aug. 1994.

[160] M. E. Marhic, I. Morita, M.-C. Ho, Y. Akasaka, and L. G. Kazovsky, "Large cross-phase modulation and four wave mixing in tellurite EDFAs," *Electron. Lett.*, vol. 35, no. 23, pp. 2045–2047, Nov. 1999.

[161] H. Masuda, A. Mori, K. Shikano, K. Oikawa, K. Kato, and M. Shimizu, "Ultra-wide-band hybrid tellurite/silica fiber Raman amplifier," in *Conf. Optical Fiber Communication, Tech. Dig. Series*, Anaheim, CA, vol. 70, 2002, pp. 388–390.

[162] L. Jiang, S. Zhenrong, Z. Xiarong, Z. Heping, X. Zhizhan, W. Zugeng, L. Jian, H. Wenhai, R. S. Armstrong, and A. P. Lay, "Optical bistability in ZnO-Nb_2O_5-TeO_2 glasses," *Opt. Mater.*, vol. 25, no. 4, p. 401, 2004.

[163] E. Yousef, M. Hotzel, and C. Russel, "Linear and non-linear refractive indices of tellurite glasses in the system TeO_2-WO_3-ZnF_2," *J. Non-Cryst. Solids*, vol. 342, no. 1–3, pp. 82–88, Aug. 15, 2004.

[164] D. Marchese, M. De Sario, A. Jha, A. K. Kar, and E. C. Smith, "Highly nonlinear GeS_2-based chalcohalide glass for all-optical twin-core-fiber switching," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 15, no. 9, pp. 2361–2370, Sep. 1998.

[165] J. A. Moon and D. T. Schaafsma, "Chalcogenide fibers: An overview of selected applications," *Fiber Integr. Opt.*, vol. 19, no. 3, pp. 201–210, 2000.

[166] R. E. Slusher, G. Lenz, J. Hodelin, J. Sanghera, L. B. Shaw, and I. D. Aggarwal, "Large Raman gain and nonlinear phase shifts in high-purity As_2Se_3, chalcogenide fibers," *J. Opt. Soc. Amer., B*, vol. 21, no. 6, p. 1146, 2004.

[167] M. Asobe, H. Kobayashi, H. Itoh, and T. Kanamori, "Laser-diode-driven ultrafast all-optical switching by using highly nonlinear chalcogenide glass fiber," *Opt. Lett.*, vol. 18, no. 13, pp. 1056–1058, Jul. 1, 1993.

[168] ——, "Third-order nonlinear spectroscopy in As_2S_3 chalcogenide glass fibers," *J. Appl. Phys.*, vol. 77, no. 11, pp. 5518–5523, Jun. 1, 1995.

[169] ——, "Laser-diode driven ultrafast all-optical switching by using a highly nonlinear chalcogenide glass fiber," *Opt. Lett.*, vol. 18, no. 13, pp. 1056–1058, Jul. 1, 1993.

[170] P. G. Kazansky, L. Dong, and P. S. J. Russell, "High second-order nonlinearities in poled silicate fibers," *Opt. Lett.*, vol. 19, no. 10, pp. 701–703, May 15, 1994.

[171] S. R. J. Brueck, X.-C. Long, and T. G. Alley, "Second-order nonlinearities in poled fibers," in *Proc. 24th Eur. Conf. Optical Communication (ECOC), (IEEE Cat. No.98TH8398)*, Madrid, Spain, vol. 3, 1998, pp. 21–25.

[172] U. Osterberg, "Photo-induced nonlinearities in optical glass fibers," in *Proc. SPIE—Int. Soc. Opt. Eng.*, Boston, MA, Sep. 1989, vol. 1171, pp. 192–200.

[173] H. Chen, C. Zhu, H. Lu, B. Yu, and F. Gan, "Photoinduced second harmonic generation of tellurite glass," *J. Mater. Sci. Lett.*, vol. 18, no. 23, pp. 1905–1906, Dec. 1, 1999.

[174] V. K. Tikhomirov, K. E. Asatryan, T. V. Galstian, R. Vallee, and A. B. Seddon, "Photoinduced birefringence in tellurite glasses," *Appl. Phys. Lett.*, vol. 84, no. 21, pp. 4263–4264, May 24, 2004.

[175] K. Tanaka, K. Kashima, K. Kajihara, K. Hirao, N. Soga, A. Mito, and H. Nasu, "Second-harmonic generation in electrically-poled TeO_2-based glasses," in *Proc. SPIE—Int. Society Optical Engineering*, San Diego, CA, 1994, vol. 2289, pp. 167–176.

[176] P. G. Kazansky, P. S. J. Russell, and H. Takebe, "Glass fiber poling and applications," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1484–1493, Aug. 1997.

[177] J. C. Knight, T. A. Birks, P. S. J. Russell, and D. M. Atkin, "All-silica single mode optical fiber with photonic crystal cladding," *Opt. Lett.*, vol. 21, no. 19, p. 1547, 1996.

[178] ——, "All-silica single mode optical fiber with photonic crystal cladding," *Opt. Lett.*, vol. 22, no. 7, p. 484, 1997.

[179] J. Fini and R. Bise, "Progress in fabrication and modeling of microstructured optical fibers," *Jpn. J. Appl. Phys. 1, Regul. Pap. Short Notes Rev. Pap.*, vol. 43, no. 8B, pp. 5717–5730, Aug. 2004.

[180] J. Broeng, D. Mogilevstev, S. E. Barkou, and A. Bjarklev, "Photonic crystal fibers: A new class of optical waveguides," *Opt. Fiber Technol.: Mater., Devices Syst.*, vol. 5, no. 3, pp. 305–330, Jul. 1999.

[181] T. A. Birks, J. C. Knight, and P. S. J. Russell, "Endlessly single mode photonic crystal fibers," *Opt. Lett.*, vol. 22, no. 13, p. 961, 1997.

[182] R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. S. J. Russell, P. J. Roberts, and D. C. Allan, "Single mode photonic bandgap guidance of light in air," *Science*, vol. 285, no. 3, p. 1537, 1999.

[183] N. A. Mortensen, "Effective area of photonic crystal fibers," *Opt. Express*, vol. 10, no. 7, p. 341, Apr. 2002.

[184] N. A. Mortensen, J. R. Jensen, P. M. W. Skovgaard, and J. Broeng, "Numerical aperture of single-mode photonic crystal fibers," *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, p. 1094, Aug. 2002.

[185] F. Vittoria, T. M. Monro, and D. J. Richardson, "The role of confinement loss in highly nonlinear silica holey fibers," *IEEE Photon. Technol. Lett.*, vol. 15, no. 9, pp. 1246–1248, Sep. 2003.

[186] W. H. Reeves, J. C. Knight, P. S. J. Russell, and P. J. Roberts, "Demonstration of ultra-flattened dispersion in photonic crystal fibers," *Opt. Express*, vol. 10, no. 14, pp. 609–613, Jul. 15, 2002.

[187] J. K. Ranka and R. S. Windeler, "Nonlinear interactions in air-silica microstructure optical fibers," *Optics Photonics News*, vol. 11, no. 8, pp. 20–25, Aug. 2000.

[188] A. M. Zheltikov, "Microstructure fibers: A new phase of nonlinear optics," *Laser Phys.*, vol. 14, no. 2, pp. 119–133, Feb. 2004.

[189] N. G. R. Broderick, T. M. Monro, P. J. Bennett, and D. J. Richardson, "Nonlinearity in holey optical fibers: Measurement and future opportunities," *Opt. Lett.*, vol. 24, no. 20, pp. 1395–1397, Oct. 15, 1999.

[190] W. J. Wadsworth, A. Ortigosa-Blanch, J. C. Knight, T. A. Birks, T.-P. M. Man, and P. S. J. Russell, "Supercontinuum generation in photonic crystal fibers and optical fiber tapers: A novel light source," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 19, no. 9, pp. 2148–2155, Sep. 2002.

[191] A. L. Gaeta, "Nonlinear propagation and continuum generation in microstructured optical fibers," *Opt. Lett.*, vol. 27, no. 11, pp. 924–926, Jun. 1, 2002.

[192] B. R. Washburn, S. E. Ralph, and R. S. Windeler, "Ultrashort pulse propagation in air-silica microstructure fiber," *Opt. Express*, vol. 10, no. 13, p. 575, Jul. 1, 2002.

[193] K. M. Hilligse, H. N. Paulsen, J. Thgersen, S. R. Keiding, and J. J. Larsen, "Initial steps of supercontinuum generation in photonic crystal fibers," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 20, no. 9, pp. 1887–1893, Sep. 2003.

[194] S. Coen, A. H. L. Chau, R. Leonhardt, J. D. Harvey, J. C. Knight, W. J. Wadsworth, and P. S. J. Russell, "Supercontinuum generation by stimulated Raman scattering and parametric four-wave mixing in photonic crystal fibers," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 19, no. 4, pp. 753–764, Apr. 2002.

[195] A. L. Gaeta, "Nonlinear propagation and continuum generation in microstructured optical fibers," *Opt. Lett.*, vol. 27, no. 11, pp. 924–926, Jun. 1, 2002.

[196] F. G. Omenetto, A. Efimov, and A. J. Taylor, "Ultrafast pulse shape driven dynamics in optical waveguides," in *Proc. SPIE—Int. Society Optical Engineering*, San Jose, CA, 2004, vol. 5340, pp. 24–36.

[197] H. Cristiani, R. Tediosi, L. Tartara, and V. Degiorgio, "Dispersive wave generation by solitons in microstructured optical fibers," *Opt. Express*, vol. 12, no. 1, p. 124, Jan. 12, 2004.

[198] K. M. Hilligsoe, T. V. Andersen, H. N. Paulsen, C. K. Nielsen, K. Molmer, S. Keiding, R. Kristiansen, K. P. Hansen, and J. J. Larsen, "Supercontinuum generation in a photonic crystal fiber with two zero dispersion wavelengths," *Opt. Express*, vol. 12, no. 6, p. 1045, Mar. 22, 2004.

[199] A. B. Fedotov, I. Bugar, D. A. Sidorov-Biryukov, E. E. Serebryannikov, D. Chorvat, Jr., M. Scalora, D. Chorvat, and A. M. Zheltikov, "Pump-depleting four-wave mixing in supercontinuum-generating microstructure fibers," *Appl. Phys., B Lasers Opt.*, vol. B77, no. 2–3, pp. 313–317, Sep. 2003.

[200] J. E. Sharping, M. Fiorentino, A. Coker, P. Kumar, and R. S. Windeler, "Four-wave mixing in microstructure fiber," *Opt. Lett.*, vol. 26, no. 14, pp. 1048–1050, Jul. 15, 2001.

[201] A. Proulx, J.-M. Menard, N. Ho, J. M. Laniel, and R. Vallee, "Intensity and polarization dependence of supercontinuum generation in birefringent and highly nonlinear microstructured fibers," *Opt. Express*, vol. 11, no. 25, p. 3338, Dec. 15, 2003.

[202] Z. Zhu and T. G. Brown, "Polarization properties of supercontinuum spectra generated in birefringent photonic crystal fibers," *J. Opt. Soc. Amer., B, Opt. Phys.*, vol. 21, no. 2, pp. 249–257, Feb. 2004.

[203] M. Fuochi, F. Poli, S. Selleri, A. Cucinotta, and L. Vincetti, "Study of Raman amplification properties in triangular photonic crystal fibers," *J. Lightw. Technol.*, vol. 21, no. 10, pp. 2247–2254, Oct. 2003.

[204] V. V. Ravi Kanth Kumar, A. K. George, J. C. Knight, and P. S. J. Russell, "Tellurite photonic crystal fiber," *Opt. Express*, vol. 11, no. 20, p. 2641, Oct. 6, 2003.

[205] H. Ebendorff-Heidepriem, P. Petropoulos, V. Finazzi, K. Frampton, R. C. Moore, D. J. Richardson, and T. M. Monro, "Highly nonlinear bismuth-oxide-based glass holey fiber," in *Proc. Optical Fiber Communication Conf. (OFC), (IEEE Cat. No.04CH37532)*, Los Angeles, CA, vol. 2, 2004, p. 3.

[206] R. K. Kumar, A. K. George, J. C. Knight, and P. S. J. Russell, "Tellurite photonic crystal fiber," *Opt. Express*, vol. 11, no. 20, pp. 2641–2645, Oct. 2003.

[207] D. J. Richardson, K. Furusawa, H. Ebendorff-Heidepriem, P. Petropoulos, V. Finazzi, J. C. Baggett, W. Belardi, T. A. Kogure, J. H. Lee, Z. Yusoff, J. Nilsson, Y. Jeong, J. K. Sahu, and T. M. Monro, "Practical applications of holey optical fibers," in *Proc. Optical Fiber Communication Conf. (OFC), (IEEE Cat. No.04CH37532)*, Los Angeles, CA, vol. 2, 2004, p. 3.

[208] C. Hao, J. Ming, Z. Huan-dong, and Z. Qing-ji, "Study on nonlinear effects in photonic crystal fibers and their applications," *Semicond. Optoelectron.*, vol. 24, no. 5, pp. 297–300, Oct. 2003.

[209] P. Petropoulos, T. M. Monro, W. Belardi, K. Furusawa, J. H. Lee, and D. J. Richardson, "2R regenerative all-optical switch based on a highly nonlinear holey fiber," *Opt. Lett.*, vol. 26, no. 16, pp. 1233–1235, Aug. 15, 2001.

[210] Z. Yousoff, P. Petropoulos, K. Furusawa, T. M. Monro, and D. J. Richardson, "A 36-channel-10 GHz spectrally sliced pulse source based on supercontinuum generation in a normally dispersive highly nonlinear holey fiber," *IEEE Photon. Technol. Lett.*, vol. 15, no. 12, pp. 1689–1691, Dec. 2003.

[211] A. V. Avdokhin, S. V. Popov, and J. R. Taylor, "Continuous-wave, high-power, Raman continuum in holey fibers," *Opt. Lett.*, vol. 28, no. 15, pp. 1353–1355, Aug. 1, 2003.

[212] F. Benabid, J. C. Knight, G. Antonopoulos, and P. S. J. Russell, "Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber," *Science*, vol. 298, no. 5592, pp. 399–402, Oct. 11, 2002.

[213] N. Akozbek and S. John, "Self-induced transparency solitary waves in a doped nonlinear photonic band gap material," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 58, no. 3, pp. 3876–3895, Sep. 1998.

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