All-Optical Signal Processing

by Fiber-Based Parametric Devices

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Parametric devices based on four-wave mixing in fibers enable the amplification, frequency conversion and phase conjugation of optical signals. They can also be used to monitor, regenerate, switch and buffer signals. The authors review recent research on these useful and versatile devices.

Optical communication systems need amplifiers to compensate for fiber loss. Current transmission systems use erbium-doped fiber amplifiers and Raman fiber amplifiers, which are phase-insensitive amplifiers. That is, they produce signal gain that does not depend on the signal phase. Parametric fiber amplifiers could also be used to amplify or process the signals. One-pump parametric amplifiers are based on degenerate four-wave mixing, whereas two-pump parametric amplifiers are usually based on nondegenerate four-wave mixing.

Parametric amplifiers can be operated in both phase-sensitive and phase-insensitive modes. Recently, the optical fiber community has shown considerable interest in parametric amplifiers, and devices based upon them, because of their favorable performance characteristics and versatility. When operated in the linear regime, parametric devices provide amplification, frequency conversion and phase conjugation. They can also generate, monitor, phase-regenerate, switch and buffer signals. When operated in the nonlinear regime, they can amplitude-regenerate signals.

Information can be encoded in a variety of formats. In amplitude-shift keyed systems, information is carried by individual pulses: The presence of a pulse denotes a 1, whereas the absence of a pulse denotes a 0. In differential phase-shift keyed systems, information is carried by neighboring pulses: Pulses with the same phase denote a 0, whereas pulses with opposite phases denote a 1. Parametric devices can process signals in both of these formats.

These devices have been made with standard single-mode fibers and single-mode fibers with small cross-sectional areas, which are often referred to as highly nonlinear fibers, and microstructured fibers.

Parametric processes in fibers

A parametric interaction driven by two pump waves (1 and 2) involves four product waves (sidebands) that are coupled by three distinct four-wave

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mixing processes. Suppose that the signal frequency $\omega_{1+} = \omega_1 + \omega$, where ω is the modulation frequency, and γ denotes a photon. Then, the modulation interaction in which $2\gamma_1 \rightarrow \gamma_{1-} + \gamma_{1+}$ produces an idler with frequency $\omega_{1-} = \omega_1 - \omega$, the phase conjugation process in which $\gamma_1 + \gamma_2 \rightarrow \gamma_{1+} + \gamma_{2-}$ produces an idler with frequency $\omega_{2-} = \omega_2 - \omega$ and the Bragg scattering process in which $\gamma_{1+} + \gamma_2 \rightarrow \gamma_1 + \gamma_{2+}$ produces an idler with frequency $\omega_{2+} = \omega_2 + \omega$.

These four-wave mixing processes are driven by nonlinearities and inhibited by dispersive and nonlinear wavenumber mismatches (which are described in the box on p. 40). By tuning the pump frequencies judiciously relative to the zero-dispersion frequency of the fiber, one can control whether modulation interaction, phase conjugation and Bragg scattering occur separately or simultaneously, as a four-sideband interaction.

Because transmission fibers are not polarization maintaining, it is important to know the polarization properties of these processes. Modulation interaction in a highly nonlinear fiber depends on the relative polarizations of the pump and signal, so a polarization-diversity scheme is required to provide signal-polarization-independent gain and frequency conversion.

In contrast, phase conjugation that is driven by orthogonal (perpendicular linearly polarized or counter-rotating circularly polarized) pumps in a highly nonlinear fiber provides gain and frequency conversion that is intrinsically polarization-independent.

Bragg scattering in a highly nonlinear fiber provides frequency conversion with an efficiency that depends on the relative polarizations of the pumps and signal. However, recent research has shown that Bragg scattering driven by co-rotating circularly polarized pumps in a rapidly spun fiber is intrinsically polarization-independent.

Hence, parametric devices based on modulation interaction, phase conjugation or Bragg scattering can all be made to operate in a polarization-independent manner.

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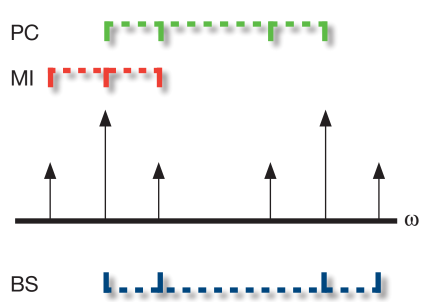
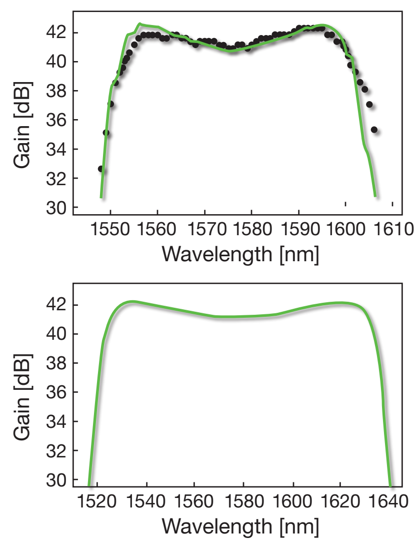
Two-sideband processes in a four-sideband interaction driven by two pump waves



Signal gain produced by phase conjugation in a highly nonlinear fiber



The circles and curves denote experimental and numerical results, respectively, for pump wavelengths of 1,540 and 1,614 nm (top). Numerical results for pump wavelengths of 1,510 and 1,648 nm (bottom).

From R. Jiang et al. OFC, paper OWB2 (2007).

For parametric devices to realize their potential as signal processors, they must amplify, convert or conjugate signals without degrading their signal-to-noise ratios significantly. In modulation interaction and phase conjugation, two pump photons are destroyed and two sideband (signal and idler) photons are produced. This behavior enables signal amplification and idler generation.

However, it also allows vacuum fluctuations associated with the idler to be amplified. As a result, excess noise is produced. (In this regard, modulation interaction and phase conjugation in a fiber are analogs of difference-frequency generation in a crystal.)

In Bragg scattering, one signal photon and one pump photon are destroyed, and one idler photon and a different pump photon are created. In other words, power is transferred from the signal to the idler.

Because the total sideband power is constant, the vacuum fluctuations are not amplified, and no excess noise is produced. (Bragg scattering in a fiber is the analog of sum-frequency generation in a crystal.)

In practice, the sideband signal-to-noise ratios are decreased slightly by spontaneous Raman scattering and noise from the erbium-doped fiber amplifiers that boost the pump or pumps. This pollutes the pumps and causes the sideband powers to fluctuate. Despite these degradations, the noise properties of parametric amplifiers are comparable to those of erbium-doped fiber amplifiers and Raman fiber amplifiers.

Applications of parametric processes

This section explores some recent experiments that show the performance capabilities of parametric devices made with fibers.

Broad-bandwidth amplification and phase conjugation

When the average of the pump frequencies $[\omega_a = (\omega_1 + \omega_2)/2]$ is comparable to the zero-dispersion frequency, phase conjugation produces high signal-gain levels with broad signal-frequency bandwidths (and Bragg scattering and modulation interaction are inhibited by dispersion). By tuning this average frequency carefully, one can control the relative importance of second-order dispersion [$\beta_2(\omega_a)$] and fourth-order dispersion [$\beta_4(\omega_a)$] to minimize the signal-frequency dependence of the gain.

In a recent experiment with a highly nonlinear fiber, phase conjugation driven by moderate-power continuous-wave pumps produced 40 dB of gain over a bandwidth of 52 nm. To put these results in perspective, note that a 10-Gb/s communication system with 64 channels, spaced by 0.4 nm, has a total signal bandwidth of 26 nm.

Thus, it is now possible to provide uniform signal gain or generate idlers, which are phase-conjugated images of the signals, with uniform efficiency, for 64-channel systems. Numerical simulations show that the same highly nonlinear fiber could provide 40 dB of gain over a bandwidth of 110 nm (which is broad enough for a fully loaded 128-channel system), if pumps with the required wavelengths were available.

In another experiment with a highly nonlinear fiber, phase conjugation driven by high-power pulsed pumps produced 23 dB of gain over a bandwidth of 95 nm.

It is now possible to provide uniform signal gain or generate idlers, which are phase-conjugated images of the signals, with uniform efficiency, for 64-channel systems.

▸ *Distant frequency conversion*

When the frequency difference between a pump and its sidebands is small, the modulation interaction is controlled by second-order dispersion. In the anomalous-dispersion regime [$\beta_2(\omega_p) < 0$, where ω_p is a pump frequency], the modulation interaction is an unstable process (which provides gain), whereas in the normal dispersion regime [$\beta_2(\omega_p) > 0$], it is a stable process. However, when the frequency difference is large, the modulation interaction is also influenced by fourth-order dispersion. If $\beta_4(\omega_p)/\beta_2(\omega_p) < 0$, the effects of second- and fourth-order dispersion cancel approximately for a narrow range of frequency differences: A high-frequency branch of the unstable modulation interaction exists.

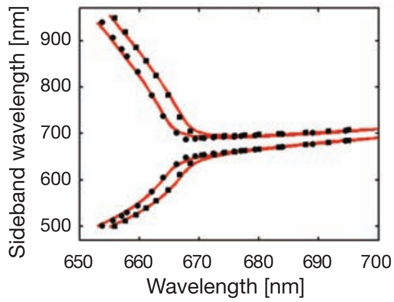
In recent experiments with microstructured fibers, modulation interactions were used to generate sidebands whose wavelengths differed by 500 nm. In others, they were used to generate idlers whose wavelengths differed from the input-signal wavelengths by 1,000 nm. Because parametric devices provide such large wavelength shifts, they allow signal generation, manipulation and detection technology for the communication band, which is centered on 1,550 nm, to be used for applications in the visible band, which is centered on 550 nm.

▸ *Distant and low-noise frequency conversion*

When the average of a pump frequency and the signal frequency is comparable to the zero-dispersion frequency, Bragg scattering transfers power efficiently from the signal to the idler (and modulation interaction and phase conjugation are inhibited by dispersion). Bragg scattering is useful because it provides tunable frequency conversion. Three recent experiments demonstrated that Bragg scattering can also provide low-noise and distant frequency conversion.

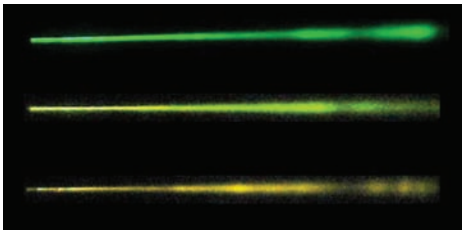
The first involved a highly nonlinear fiber. Pumps at 1,566 and 1,598 nm were used to transfer power from a signal at 1,588 nm to the Bragg-scattering idler at 1,556 nm (32-nm wavelength shift), with an efficiency of 0.99 (neglecting the 1.5-dB total loss). The optical signal-to-noise ratio of the Bragg-scattering idler was measured and compared to those of

[Modulation interactions in microstructured fibers]



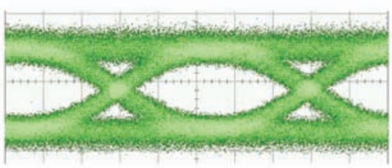
Sideband wavelengths as functions of the pump wavelength. The curves denote theoretical predictions, and the circles and squares experimental results.

From A. Chen et al. Opt. Lett. **30**, 762-4 (2005).



Free-space idlers generated by a 1,542-nm signal. As the pump wavelength varied from 790 to 842 nm, the idler wavelength varied from 530 (green) to 580 nm (yellow).

From R. Jiang et al. IEEE Photon. Technol. Lett. **18**, 2445-7 (2006).



Measured eye diagram of the 512-nm idler generated by a 1,575-nm signal and a 780-nm pump. Amplitude-shift-keyed data was transmitted at 1 Gb/s.

From R. Jiang et al. OFC, paper OWQ4 (2007).

a phase-conjugation idler and a signal amplified by an erbium-doped fiber amplifier. The signal-to-noise ratio of the Bragg-scattering idler was higher by more than 2 dB. These results demonstrate that Bragg scattering is a low-noise process.

The second experiment involved a dispersion-shifted single-mode fiber. Pumps at 1,420 and 1,620 nm were used to transfer power from a C-band signal at 1,545 nm to an O-band idler at 1,365 nm (180-nm wavelength shift, shown by large triangles).

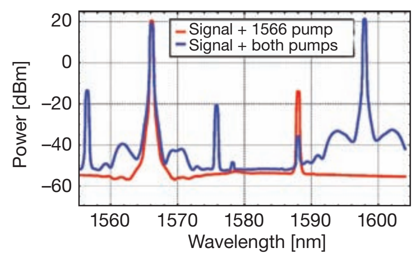
The dispersion profiles of fibers allow wavelength shifts of several hundred nanometers. In this experiment, the shift was limited only by the pumps available to drive the Bragg-scattering process.

The third experiment involved a highly nonlinear fiber. Pumps at 1,540 and 1,605 nm were used to transfer information from an L-band signal at 1,567 nm to an S-band idler at 1,515 nm. Amplitude-shift keyed data was transferred successfully at 2.5 Gb/s.

Low-noise frequency conversion is a useful function for classical communication systems, because it allows signals to be distributed optimally among the available channels. It is also an indispensable function for quantum communication systems.

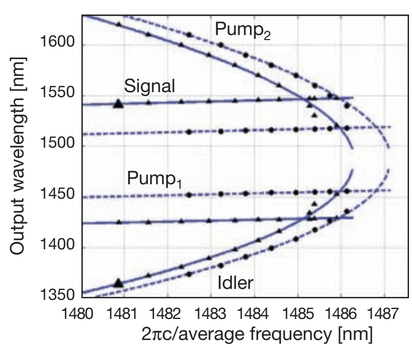
In such systems, qubits are stored by atoms or ions, which absorb and emit signal photons with wavelengths in the range of 800 to 1,000 nm. Unfortunately, in this range the fiber loss rate is too high for faithful long-distance transmission. Low-noise frequency conversion enables the transfer of qubits from signal photons to idler photons whose wavelengths are in the low-loss windows centered on 1,310 and 1,550 nm. After transmission, low-noise frequency conversion returns the qubits to their original wavelengths.

[Bragg scattering provides low-noise frequency conversion]



Spectra produced by two pumps and a signal in a highly nonlinear fiber.

From A. Gnauck et al. Opt. Express **14**, 8989-94 (2006).



Phase-matching curves for Bragg scattering in a micro-structured fiber. Output wavelengths as functions of the average wavelength. Dashed and solid curves represent theoretical predictions, whereas circles and triangles represent experimental results with different P_1-S wavelength differences.

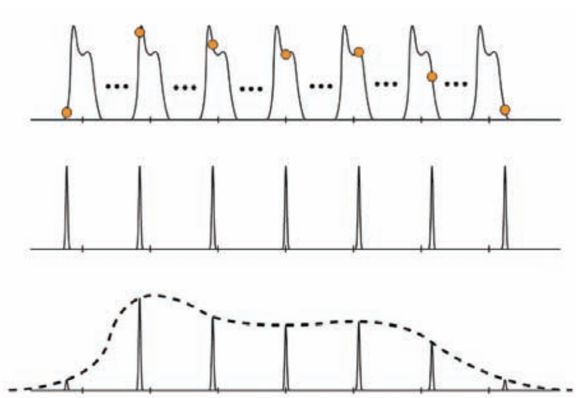
From D. Méchin et al. Opt. Express **14**, 8995-9 (2006).

▸ *Monitoring by four-wave mixing*

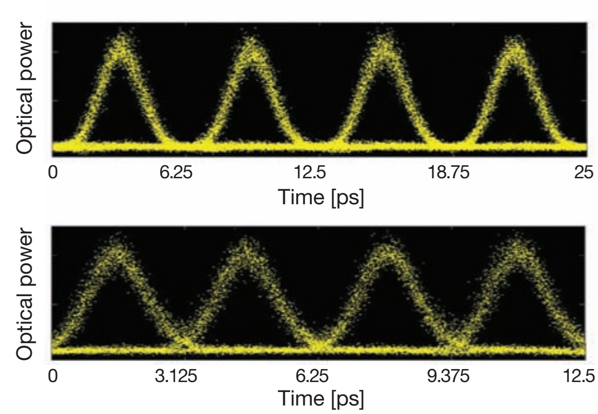
In each of the aforementioned applications, the nonlinear interaction of the pump and signal produces an idler. One can use this phenomenon to sample pulses nondestructively.

Consider a train of similar pulses, and suppose that the pump is turned on and off on a timescale that is short compared to the pulse duration. Then modulation interaction produces a train of short idler pulses, whose peak powers are proportional to the signal powers at the instant they were sampled. If the time interval between the samples differs slightly from the bit period, the illuminated regions of the signal pulses change from the fronts to the middles and backs of the pulses: The train of signal pulses is sampled stroboscopically. Because the train of idler pulses extends over several bit periods (one pulse per bit period), it can be measured using a slow detector. (Measuring an individual pulse requires

[Stroboscopic sampling of pulse trains]



Train of signal pulses (top), train of short pump pulses (center) and train of short idler pulses (bottom).



Measured eye diagrams of 160-Gb/s (top) and 320-Gb/s (bottom) signal trains.

From M. Westlund et al. J. Lightwave Technol. **23**, 2012-22 (2005) and by courtesy of PicoSolve.

a fast detector, whose response time is a small fraction of the bit period.)

▸ *Amplitude regeneration by gain saturation*

In most applications, parametric amplifiers are operated in the linear regime. However, those that are operated in the nonlinear (pump-depletion) regime can be used to clean-up (regenerate) noisy signals. Because the output signal power depends sub-linearly on the input power, noise-induced variations in the input 1-levels of amplitude-shift keyed signals are reduced.

Unfortunately, the input 0-levels experience linear gain, so their noise-induced variations are amplified by the same amount as the mean signal: The extinction ratios of the output signals are low (as are the extinction ratios of the primary idlers produced by pump-signal four-wave mixing).

However, if the pump and signal powers are sufficiently high, secondary sidebands are produced by signal-idler four-wave mixing. The 0-levels of these sidebands (idlers) experience super-linear gain, so their noise-induced variations are amplified less than the mean signal: By using higher-order four-wave mixing, one can generate secondary idlers (output signals) with high extinction ratios. This regeneration method is currently limited to single-channel systems.

▸ *Phase regeneration by phase-sensitive amplification*

Many performance records have been set recently by differential phase-shift keyed systems. Their main impairment is phase jitter, which is driven by amplifier noise, or pulse collisions, and is mediated by nonlinearity. Phase jitter can be reduced by phase-sensitive amplification, because the in-phase signal components (which define the average phase and carry information) are amplified, whereas the out-of-phase components (phase fluctuations) are attenuated.

Phase-sensitive amplification is produced by cross-phase modulation in a fiber interferometer. In the absence of a signal, all of the pump power is emitted by one of the output ports. In the presence of a signal, cross-phase modulation allows power to be emitted at the other output port. The amount of cross-phase modulation depends on the pump and signal powers, and their relative phase. In recent experiments, this scheme was used to remove the phase noise from differential phase-shift keyed signals. Phase-sensitive amplification is also produced by four-wave mixing. This regeneration method is currently limited to single-channel systems.

▸ *Impairment reduction by phase conjugation*

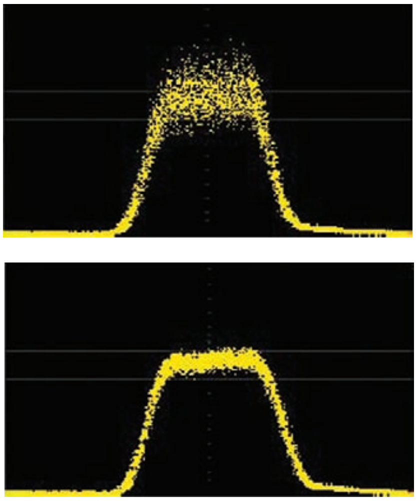
Light-wave propagation in fibers is governed approximately by the nonlinear Schrödinger equation for the wave amplitude A. Suppose that a phase conjugation device receives the complex amplitude A, and transmits the conjugate amplitude A*. Then A* is governed by the conjugate nonlinear Schrodinger equation, which is just the original equation with the sense of propagation reversed: Pulse perturbations that increase before the phase conjugation, and would, if unabated, impair the transfer of information, decrease after it. For this reason, phase conjugation can reduce a variety of impairments (linear and nonlinear) simultaneously. Phase conjugation is reviewed in the references.

▸ *Buffering by frequency conversion and dispersion*

It is well known that one can buffer (delay) signals by combining frequency conversion and dispersion. The time delay is proportional to the product of the frequency shift of the signal and the

Parametric amplifiers that are operated in the pump-depletion regime can be used to regenerate noisy signals.

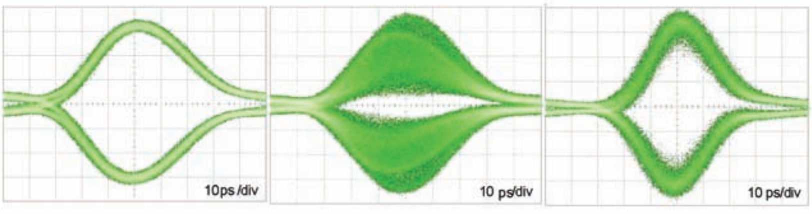
[Amplitude regeneration]



Pumps at 1,567 and 1,604 nm, and a signal at 1,583 nm, produced primary and secondary idlers at 1,587 and 1,576 nm, respectively. Power profile of the noisy input signal (top) and power profile of the regenerated secondary idler (bottom).

From S. Radic et al. IEEE Photon. Technol. Lett. **15**, 957-9 (2003).

[Phase regeneration]



Data without phase noise (left), with added phase noise before regeneration (middle) and with added phase noise after regeneration (right).

From K. Croussore et al. Opt. Express **13**, 3945-50 (2005).

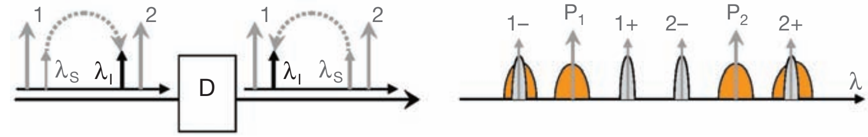
[Frequency and wavenumber matching]

Consider the four-wave mixing process in which two input photons γ_1 and γ_2 are destroyed, and two output photons γ_3 and γ_4 are created. In this process, the conservation of energy is manifested by the frequency-matching condition $\omega_1 + \omega_2 = \omega_3 + \omega_3$, and the conservation of momentum is manifested by the wavenumber-matching condition $k_1 + k_2 = k_3 + k_4$, where each wavenumber is a function of frequency [$k_j = k(\omega_j)$].

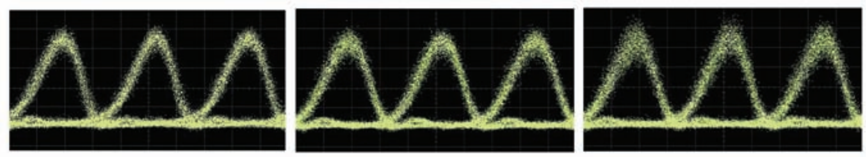
In the absence of dispersion, each wavenumber depends linearly on the associated frequency, so the wavenumber-matching condition is satisfied whenever the frequency-matching condition is satisfied. However, in the presence of dispersion, the frequency dependence of the wavenumber is more complicated, and frequency matching does not guarantee wavenumber matching: four-wave mixing only occurs for certain values of the input and output frequencies.

To model four-wave mixing quantitatively, one chooses a reference frequency ω_r, which is usually related to the input frequencies, and writes $k_j(\omega_j) = \Sigma_n \beta_n(\omega_r)(\omega_j - \omega_r)^n/n!$, where $\beta_n = d^n k/d\omega^n$ is the nth-order dispersion coefficient. A wide range of fiber experiments can be modeled by retaining the first four dispersion coefficients. Because fibers are nonlinear media, each wavenumber also acquires contributions that are proportional to the powers of the interacting waves. These contributions modify the wavenumber-matching condition.

[Buffering by phase conjugation and dispersion]



Phase-conjugation-based scheme for producing tunable delays (left). Signal and idler spectra produced by counter-phased pumps (right).



Measured eye diagrams of a 10-Gb/s amplitude-shift-keyed signal delayed by 0 ns (left), 6.8 ns (middle) and 12.5 ns (right).

From J. Ren et al. ECOC, paper Th4.4.3 (2006).

dispersion coefficient of the fiber. If the shift is tunable, so too is the delay.

In a recent implementation of this scheme, modulation interaction was used to provide the frequency shift and produce a delay of 0.8 ns. However, parametric pumps need to be phase-modulated to suppress stimulated Brillouin scattering. Although pump-phase modulation does not affect the spectrum of the signal amplified by modulation interaction, it broadens the spectrum of the generated idler, which is a frequency-shifted copy of the signal.

When the idler propagates through the dispersive fiber, these phase fluctuations are converted into amplitude fluctuations, which impair the transfer of information. This problem can be avoided by the use of phase conjugation driven by counter-phased pumps, or Bragg scattering driven by co-phased pumps, to provide the frequency shift.

Buffering by phase conjugation is a three-step process. First, phase conjugation is used to shift the input-signal frequency (generate an idler), without broadening its spectrum. Second, the idler is passed through a dispersive fiber, which delays it. Third, phase conversion shifts the idler frequency to the input frequency (restores the signal).

The idler is a conjugated copy of the input and output signals. Hence, one can reverse the pulse broadening that occurs when the idler passes through the dispersive fiber by passing the output signal through a similar fiber. As the wavelength shift varied from 0 to 20 nm, the time delay varied from 0 to 12.5 ns. In all cases, the output eyes were open, which demonstrated the high quality of the output signals.

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