# Fiber-Based Nonlinear Processing of Optical Signals

R. M. Jopson, A. H. Gnauck, C. J. Mckinstrie

Crawford Hill Lab, Bell Laboratories, Alcatel-Lucent, virgin@alcatel-lucent.com

**Abstract** *Optical processing in fiber has enabled recent advances such as large, tuneable signal delays, the shifting of signals to mid-IR wavelengths, and the creation of specific quantum states useful in sensing, imaging, and communication applications.*

## Introduction

The invention of the optical maser and subsequent explosion in laser research, discovery of new laser lines, and commercial development of lasers provided unprecedented access to high-power, narrow-spectrum light. This enabled observation and use of weak optical nonlinearities in materials. Among the early uses of optical nonlinearity[1] was frequency doubling or sum-frequency generation in crystals such as potassium dihydrogen phosphate (KDP). Such crystals facilitated the attainment of nonlinearity and phase matching, two conditions necessary to achieve usable optical nonlinearity. The nonlinearity generally arises from intense optical fields driving electrons into significantly anharmonic regions of their potential. Nonlinear response of the nuclei also contributes to the nonlinearity. For some optical nonlinearity, phase matching is required to ensure that light generated throughout the interaction region adds coherently. In nonlinear crystals, phase matching is often obtained through exploitation of the crystal birefringence.

The amount of light generated by nonlinear interaction can be increased by focusing the available power to a narrow beam waist. However this shortens the confocal parameter and hence shortens the interaction length. This problem can be avoided by using a waveguide such as optical fiber to confine the light (see Stolen and Bjorkholm[2] and references therein). Optical fiber generally has much lower nonlinearity than nonlinear crystals, but this weakness is more than compensated by the possibilities of a small mode area with a very long interaction length, 1 km or longer. Phase matching is generally achieved in nonlinear fiber by careful control of the fiber dispersion profile. Several approaches to making highly nonlinear fiber have been tried with varying success. Silica fiber manufacture is a mature technology, so the best results for many applications have been achieved by making silica fiber with a small mode area[3]. Other nonlinear fibers have been made with materials having a much higher nonlinearity such as bismuth oxide[4], chalcogenides[5], and silica doped with lead or other nonlinear material. Photonic crystal fibers of various designs and materials[5] are also used. In addition to optical fiber, short nonlinear waveguides in such materials as periodically-poled lithium niobate (PPLN)[6] and silicon[7] can provide nonlinear interaction.

Among the nonlinear effects that occur in optical fiber[8] are Brillouin scattering, Raman scattering, and manifestations of the Kerr nonlinearity variously known as self-phase modulation, cross-phase modulation, four-wave mixing or four-photon mixing, modulation instability, Bragg scattering, phase conjugation, and nonlinear polarization rotation. All of these effects have been used for optical processing.

## All-Optical Delay

The ability to delay or buffer signals by variable amounts of time is a fundamental requirement in telecommunication networks and other applications. Recently, the generation of tunable optical delay has been advanced significantly though the use of fiber parametric amplifiers. A lengthy, ongoing effort to accomplish these delays in bulk media using "slow light" phenomena had achieved a variation in delay of only a small number of bits. Then a spirited effort ensued to achieve large optical delays via frequency shifting in parametric amplifiers implemented in periodically-poled lithium niobate, silicon waveguides or silica fiber [6, 7, 9-12]. The pace of advancement has been rapid, as evidenced by the representative sample of results shown in Fig. 1. The results shown were achieved either using a 10-Gb/s or faster signal or in an apparatus with a bandwidth suitable for at least a 10-Gb/s bit rate. The bandwidth is important because a fundamental limit in the “slow-light” approach is the product of the delay time and the available signal bandwidth. This is proportional to the number of bit slots of delay that can be achieved. As can be seen in Fig. 1, the parametric gain approach has achieved delays exceeding 60,000 bit slots.

The basic principle of these schemes is

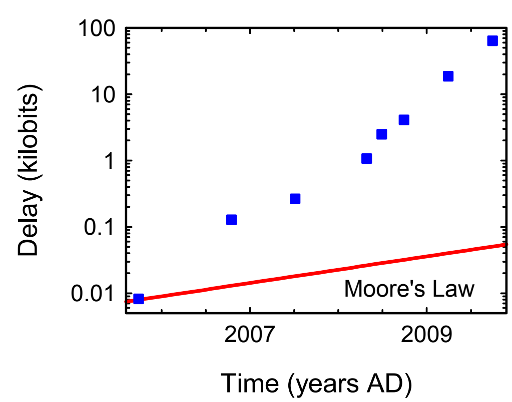


**Fig. 1:** The rate of increase in tunable delay range achieved by waveguide-based parametric processors in silica, silicon and periodically-poled lithium niobate greatly exceeds the rate associated with Moore's Law.

978-3-8007-3173-2 

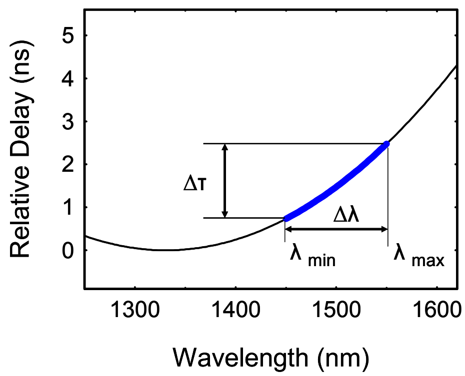


**Fig. 2:** Schematic illustrating variable optical delay in a 1-km long standard fiber. The parabola shows the relative delay for 1 km of standard fiber. When the transmission wavelength is shifted by Δλ from $\lambda_{min}$ to $\lambda_{max}$, the transmission delay changes by Δτ. In a delay device, the wavelength must be shifted back to the input wavelength or some other fixed wavelength.

illustrated in Fig. 2. A signal first passes through a parametric wavelength shifter, then a dispersive component such as a length of optical fiber. Since the group delay of the dispersive component changes with changes in wavelength, the transmission delay can be adjusted by changing the amount by which the wavelength of the signal is shifted. A second wavelength shifter is needed to shift back to the input wavelength or some other desired wavelength for the output. The change in propagation delay, Δτ, caused by shifting the wavelength of a signal transmitted through a fiber of length $L$ having a spectrally flat chromatic-dispersion parameter, $D$, is $\Delta\tau = LD\Delta\lambda$ where Δλ is the change in wavelength. It can be seen from Fig. 2, that for a 100-nm accessible range for wavelength shifting, about 1000 km of standard fiber would be required to provide the record 1.8-μs delay range that has been demonstrated so far[13]. Clearly, fiber with high-dispersion, such as dispersion-compensating fiber, is advantageous.

Unfortunately, in addition to facilitating variable delay, the dispersion also distorts the signal. This limits the tuning range of the delay. For example, a non-return-to-zero (NRZ), on/off-keyed (OOK) signal of bit rate B incurs penalty of less than 1 dB so long as $|D|L < c/(\lambda B)^2$, where $c$ is the speed of light, λ is the wavelength of the signal, and $|D|$ is the magnitude of $D$. Inserting this into the expression for Δτ above, we find that to incur less than a 1-dB dispersion penalty, the delay change is limited to

$$\Delta\tau < \Delta\lambda c/(\lambda B)^2.$$

Thus, if the parametric wavelength shifter can achieve a maximum shift of $\Delta\lambda_{max}$, the maximum delay range, $\Delta\tau_{max}$, is given by

$$\Delta\tau_{max} = \Delta\lambda_{max}\, c/(\lambda B)^2.$$

Fig. 3 shows the maximum delay range available for the NRZ, OOK signal mentioned above, assuming

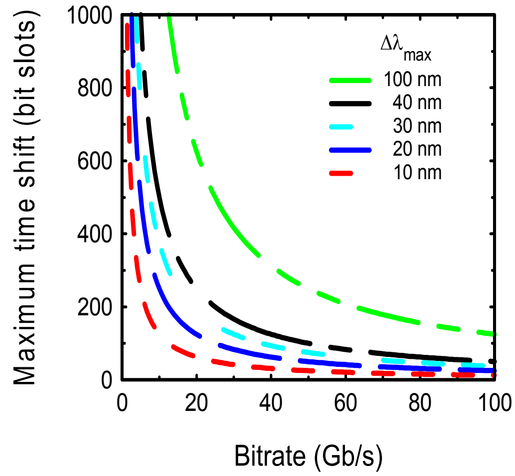


**Fig. 3** Maximum time shift available for a penalty less than 1 dB when dispersion compensation is not employed, for non-return-to-zero, on/off modulation and chromatic dispersion with vanishing higher-order terms. $\Delta\lambda_{max}$ is the tunable range of the wavelength shift. The legend is in the same order as the curves.

spectrally flat dispersion. If the dispersion is not spectrally flat, the available delay range is reduced. This is because the amount of dispersion is limited by $D_{max}$, the maximal value of the magnitude of $D$ in the required wavelength tuning range, while the maximal delay is determined by $D_{mean}$, the mean value of $D$ in the tuning range. Thus the expression above for the maximum achievable delay range becomes

$$\Delta\tau_{max} = |D_{mean}/D_{max}| \cdot \Delta\lambda_{max}\, c/(\lambda B)^2 .$$

For dispersion slope per unit length, $S$, (and vanishing orders of dispersion higher than slope),

$$| D_{mean}/D_{max}| = 1 \;/\; (1+ |S/D_{mean}| \cdot \Delta\lambda_{max}/2)$$

Thus the dispersion slope will reduce the maximum achievable delay by about 20% for $\Delta\lambda_{max}$ = 100 nm when using standard single-mode fiber (SMF) or other fiber, such as slope-matched dispersion-compensating fiber for SMF, having the same ratio of dispersion slope to dispersion. Note that the expressions above require modification for the self-defeating case of $D$ changing sign within the wavelength tuning range.

Fig. 3 shows that chromatic dispersion places stringent limits on the achievable delay for high-bit-rate signals. For instance, the delay of a 40-Gb/s signal is limited to a tuning range of about 300 bits, even when $\Delta\lambda_{max}$ is as much as 100 nm. The addition of dispersion compensation can relax this limitation. Dispersion compensation could require considerable amounts of fiber. For instance, a demonstration of 4000 bits of delay at 10 Gb/s[10] required a dispersive element providing 9800 ps/nm of dispersion. This was provided by 71 km of fiber with a large, negative dispersion parameter, $D$. However, compensation with positive-$D$ fiber, which is not readily available with large values of $D$, would have required 600 km of standard fiber. To avoid these long lengths with their attendant loss and latency, mid-span phase conjugation[14,15] has been employed[10,12] to compensate the dispersion. This permits the use of the highly dispersive negative-*D* fiber for both the creation of variable delay and the compensation of the resulting dispersion. The signal is shifted to the variable wavelength and transmitted through the highly dispersive fiber. It is then shifted with phase conjugation back to the original wavelength and transmitted through the highly dispersive fiber again. The dispersion can be compensated exactly if the dispersive element is spectrally flat, but dispersion variation can limit the usable delay. When using dispersion having a slope but no higher-order dispersion terms,

$$\Delta\tau_{max} = 2\,|D_{mean}/S| \cdot c/(\lambda B)^2 .$$

The leading factor of two is gained by adding a "bias" compensation to center the dispersion impairment on the tuning range. Note that for this case, the dispersion-limited delay range does not depend on the wavelength-tuning range, but the amount of dispersive fiber required to achieve it does. Dispersion compensation increases the accessible delay by a factor of 10 or more, but heroic effort in dispersion slope equalization must be made to push the technique further. For instance, if the magnitude of the slope-to-dispersion ratio in the highly dispersive fiber is 10% that of standard fiber, a 40-Gb/s NRZ OOK signal is limited to a delay range of about 13000 bits.

The limit imposed by dispersion slope was overcome by Namiki who realized that by adding an

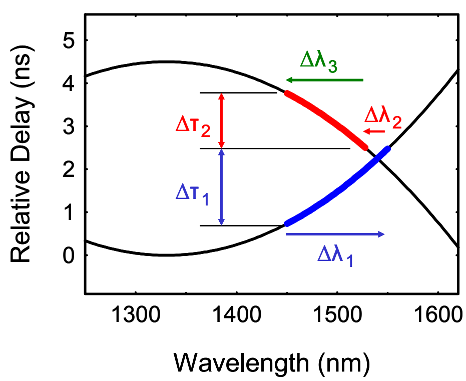


**Fig. 4:** Schematic illustrating a practical scheme for achieving long variable optical delay. The parabolas show the relative delay of 1 km of standard fiber with the upper profile inverted for the purpose of illustration. The first wavelength shift, $\Delta\lambda_1$ is determined largely by the desired delay. The second wavelength shift, $\Delta\lambda_2$ is chosen to minimize the total signal dispersion. This shift is accompanied by phase conjugation to allow the second delay to compensate dispersion. The third wavelength shift, $\Delta\lambda_3$ returns the signal to the input wavelength and conjugates the phase. The variable part of the delay is $\Delta\tau_1 + \Delta\tau_2$.

additional wavelength shift, dispersion could be compensated exactly at each point in the delay tuning range.[16,17] The method is illustrated in Fig. 4. As before, the signal is shifted by $\Delta\lambda_1$ to the variable wavelength and transmitted through the highly dispersive fiber. Dispersion could be compensated exactly, if at this point, the signal was phase-conjugated without a change in wavelength and transmitted through an identical highly-dispersive fiber. In practice, a small wavelength shift, $\Delta\lambda_2$ accompanies the phase conjugation and the signal is then transmitted through the highly dispersive fiber again before being phase conjugated and wavelength shifted by $\Delta\lambda_3$ back to the input wavelength. A small "bias" dispersion compensates the difference in dispersion for the two trips through the highly dispersive fiber. The net dispersion can be made arbitrarily small by proper choice of $\Delta\lambda_2$. This technique was implemented with a 40-Gb/s return-to-zero differential-phase-shift-keyed (RZ-DPSK) signal to achieve the current record of 62400 bits of continuously tunable delay range.[18]

**Large wavelength shifts**

Nature often constrains the wavelength of light that can be used for some desired application to a spectral region where we have limited ability to manipulate and measure light. Optical fiber nonlinearity can be used to translate carefully prepared light at one wavelength to another. For instance, tremendous activity in optical telecommunications over the last few decades has resulted in an unparalleled ability to create, prepare, manipulate and measure light in the telecommunications band near 1550-nm. However, optical communication through sea water is best done at blue-green wavelengths where little telecommunications technology has been developed. A group at UCSD demonstrated translation from the telecommunications band to green light[19], for instance from 1542 nm to 531 nm, using parametric amplification in a photonic-crystal fiber. A detector-bandwidth-limited 155-Mb/s non-return-to-zero (NRZ) on-off-keyed signal was successfully received with a bit-error rate (BER) less than $10^{-7}$.

In another demonstration, the same group shifted light from the telecommunications band to longer wavelengths[20]. The short-wave infrared band (SWIR band) is useful in LIDAR (light detection and ranging) and other sensor applications. Neither sources nor detectors have performance in this band that approaches performance available in the telecommunication band. The feasibility of converting telecommunications-band light to high-power SWIR light was demonstrated[21] using an 8-m length of highly nonlinear silica fiber selected to provide phase matching over a broad bandwidth. The high-power pump had a wavelength near 1590 nm, a pulse width of 1 ns and a duty factor of 1/1100. The low-duty factor allowed amplification to peak powers around +55 dBm in an erbium-doped fiber amplifier. The seed was a CW source with a wavelength tuned between 1260 nm and 1360 nm. This tuning range generated wavelengths between 2150 nm and 1900 nm with peak powers between +44 and +48 dBm. A typical output spectrum is shown in Fig. 5. The measured power has been normalized to show peak power. This demonstration did not require modulation of the pump light other than pulsing, but in principle, amplitude or phase modulation could be impressed on the SWIR pulses by suitable modulation of the 1-ns pump pulses.

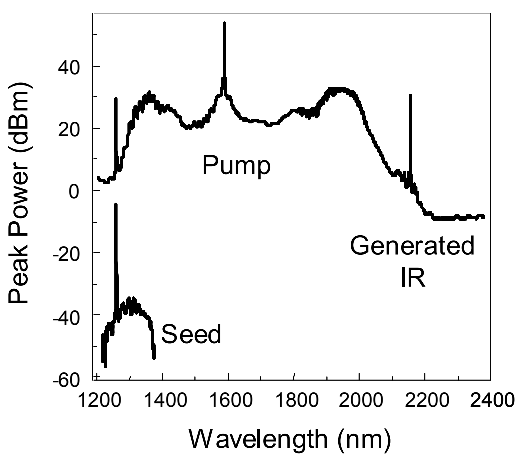


**Fig. 5:** Generation of short-wave infrared light in a highly-nonlinear silica fiber, showing the output spectrum of CW power without pump (lower curve) and the spectrum of peak power with pump light (upper curve). The pump had a peak power of 170 W.

**Single-photon sources**

Entangled-photon sources and single-photon sources derived from them are useful for quantum-key distribution and other quantum technology applications. The traditional source of entangled photons has been pair production in nonlinear crystals. In addition to the packaging problems that are important when these sources are developed commercially, these bulk optic sources often have poor collection efficiencies into beams and fiber waveguides. There has long been an effort[22-26] to use fiber nonlinearity to generate photon pairs. This has resulted in high-brightness sources with reasonable fidelity. Efforts were soon devoted to improving the quality of the states produced. Two recent reports used a carefully selected dispersion profile to tailor the purity of the entanglement.[27,28] This allowed the direct generation of heralded pure photon states without requiring narrow filters and the attendant loss in throughput. These achievements were enabled by the flexibility in phase matching offered by optical fibers.

**Summary**

The low loss and tight confinement of optical fiber allows the small fiber nonlinearity to be used in a multitude of applications. Dispersion tailoring in standard fibers and photonic crystal fibers has allowed access from the 1550-nm telecommunications band to a bandwidth spanning two octaves. Optical fiber nonlinearity has been used to achieve unprecedented all-optical delays. Paradoxically, fiber nonlinearity has been used in applications requiring extremely low powers such as single-photon sources. The exploitation of optical fiber nonlinearity will continue to delight and amaze us.

**References**

1 B. G. Huth et al., *Spectrosc. Lett.* **1**, 425 (1968).
2 R. H. Stolen and J. Bjorkholm, *J. Quant. Electron*. **18**, 1062 (1982).
3 T. Nakanishi et al., *IEICE Tech. Rep.* **106**, 41, paper OCS2006-81 (2007).
4 K. Kikuchi et al., *Electron. Lett*. **38**, 166 (2002).
5 C. B. Chaudhari, *Proc. OFC'09,* OTuC4 (2009).
6 Y. Wang et al., *Proc. ECOC'05,* Th1.3.3-2 (2005).
7 Y. Okawachi et al., *Opt. Express* **16**, 10349 (2008).
8 G. P. Agrawal, *Nonlinear Fiber Optics, 4th Edition*, Elsevier (2007).
9 J. Ren et al., *PD Proc. ECOC'06*, Th4.4.3 (2006).
10 E. Myslivets et al., *Photon. Technol. Lett.* **21**, 251 (2009).
11 L. Christen et al., *Proc. OFC'08*, OTuD1 (2008).
12 N. Alic et al., *Photon. Technol. Lett.* **20**, 1187 (2008).
13 N. Alic et al., *OFC'09*, PDPA1 (2009).
14 S. Watanabe et al., *Photon. Technol. Lett.* **5**, 92 (1993).
15 S. Radic et al., *OFC'03*, PD-3 (2003).
16 S. Namiki, *J. Lightwave Technol.* **26**, 28 (2008).
17 S. Namiki and T. Kurosu, *Proc. ECOC'08*, PDP Th3.C.3 (2008).
18 Evgeny Myslivets et al., *Opt. Express* **17**, 11958 (2009).
19 R. Jiang et al., *Photon. Technol. Lett.* **18**, 2445 (2006).
20 J. M. Chavez Boggio et al., *Opt. Express* **16**, 5435 (2008).
21 J. M Chavez Boggio et al., Private communication.
22 M. Fiorentino et al., *Photon. Technol. Lett*. **14**, 983 (2002).
23 H. Takesue and K. Inoue, Phys. Rev. A **72**, 041804 (2005).
24 K. F. Lee et al., Opt. Lett. **31**, 1905 (2006).
25 J. Fulconis et al., New J. Phys. **9**, 276 (2007).
26 Alexander Ling et al., quant-ph arXiv:0906.3328v2 (2009).
27 Offir Cohen et al., *PRL* **102**, 123603 (2009).
28 M. Halder et al. *Opt. Express* **17**, 4670 (2009).