Noise-reduction capabilities of a Raman-mediated wavelength converter

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We describe ultrawideband Raman-mediated wavelength conversion. The nonlinear conversion transfer function is calculated analytically and simulated numerically in the cw regime, and the predicted performance is confirmed experimentally. Data conversion from long- to short-wavelength bands with signal reshaping and significant noise reduction are demonstrated experimentally at 10 Gbit/s and modeled by numerical simulations. Q factors and extinction ratios that are both larger than 10 dB are possible over an effective conversion bandwidth of 35 nm. © 2003 Optical Society of America

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The vast growth in demand for information capacity in optical fiber systems and networks has initiated an extension of operational wavelengths into new regimes of the fiber spectrum. The so-called C band (1530–1565 nm) in which standard erbium-doped fiber amplifiers (EDFAs) operate has been extended to the L band (1565–1625 nm), where modified EDFAs can be implemented. Recent advances have pushed researchers beyond the L band into the U band (1625–1675 nm), while at the same time short wavelengths in the so-called S band (1480–1530 nm) have also been exploited. Operation in such widely separated wavelength ranges requires the development of several key components, the most important ones being sources, wideband amplifiers, and flexible wavelength-converting devices that can also serve as all-optical reshaping elements. This Letter describes a new all-optical wavelength converter with reshaping capabilities. The device is based on nonlinear cross talk mediated by saturation of the Raman effect in an optical fiber. Wavelength conversion over 13 THz, from L to S bands, of 10-Gbit/s data, with significant reshaping and noise reduction, are demonstrated experimentally and modeled by numerical simulation.

The wavelength converter is composed of a highly nonlinear fiber (HNLF) that has two inputs: a strong modulated signal whose wavelength is longer than that of a cw probe by the Stokes Raman shift (~13.2 THz). As the two signals propagate down the fiber, the probe is modulated because of Raman-mediated depletion, and when the walk-off between the two is negligible, the probe reproduces, at the fiber output, the complementary data sequence of the signal.

Using the cw power equations for the Raman effect in a strongly depleted regime ($P_s \gg P_{pr}$), we find that the probe power at the output of a fiber whose length is $L$ is given by

$$P_{pr}(L) = P_{pr}(0)\exp[-\alpha_{pr} L - C_R P_s(0)L_{eff}^s],$$  \hspace{1cm} (1)

where

$$L_{eff}^s = \frac{1 - \exp(-\alpha_s L)}{\alpha_s};$$  \hspace{1cm} (2)

$P_s$ and $P_{pr}$ are, respectively, the signal and probe powers; $\alpha_s$ and $\alpha_{pr}$ are the fiber loss coefficients at the signal and probe frequencies, respectively; and $C_R$ is the Raman gain efficiency coefficient. For low signal power, the probe experiences only fiber loss, whereas high signal power induces significant depletion, so the probe decreases exponentially with interaction length up to the fiber effective length, $L_{eff}^s$. Since the Raman effect has a quasi-instantaneous response, Eq. (1) is valid for modulated signals, and since it has a nonlinear form, it predicts the capability to reduce noise fluctuation.

Perfect complementary mapping of the wavelength-converted data requires that the walk-off between the probe and the signal be negligible in comparison with the operating bit period. Because of the large Stokes shift, the only way to reduce the walk-off is to operate almost symmetrically near the zero-dispersion wavelength, and this may limit the operational bandwidth of the system. Also, a large extinction ratio (ER) of the converted data at the probe wavelength requires a high signal power, and this may cause anti-Stokes spontaneous-emission noise that can degrade the quality of the data that are imprinted on the probe. However, the large Raman shift makes this a negligible effect.

The experimental setup is shown in Fig. 1. The input is two tunable laser sources; one acts as the probe in the S band, with a tuning range 1480–1495 nm and power less than 0 dBm. The second serves as the signal in the L band (1584 nm). The long-wavelength signal is modulated at a bit rate of 10 Gbit/s by an integrated amplitude–phase modulator. Phase modulation at 100 MHz is needed to eliminate stimulated Brønllin scattering. The modulator has two outputs: one is coupled to a high-power L-band EDFA followed by a bandpass optical filter. The average power at the filter output is ~19.5 dBm. The second output reproduces the complementary data sequence and is used for monitoring. The signal and the probe feed a 4-km-long HNLF through a 1480-nm–1550-nm wavelength-division multiplexed coupler. The HNLF has an effective area of $A_{eff} \sim 12 \mu m^2$ and a nonlinear coefficient of $\gamma \sim 10.6 W^{-1}/km$. Its zero-dispersion...
wavelength is $\lambda_0 = 1536.3$ nm, its dispersion slope at $\lambda_0$ is 0.018 ps/nm$^2$ km, and the losses are $\alpha_s = 0.75$ dB/km and $\alpha_{pr} = 0.85$ dB/km. A second wavelength-division multiplexed coupler separates the two wavelengths at the fiber output, and the probe is coupled to a receiver.

The first experiment was a measurement of the cw depletion transfer function. The two signals were separated by the Stokes shift, and the depletion of the short-wavelength power was measured as a function of the long-wavelength power coupled to the HNLF. The measured transfer function is compared in Fig. 2 with the expression

$$D[P_s(0)] = \frac{P_{pr}(L)}{P_{pr}(0)} \exp(-\alpha_{pr}L) = \exp(-C_R P_s(0)L_{eff}^s),$$

and the function shows exponential growth of the depletion that becomes significant for input powers greater than +5 dBm. Also, fitting the measured data with the analytical expression [Eq. (3)] enables us to extract the value of $C_R$, which turns out to be approximately 3.7 W$^{-1}$/km. Figure 2 also describes the measured dependence of the converted extinction ratio (ER) on the signal input power for a 10-Gbit/s data sequence. The ER increases exponentially, consistent with the cw depletion function [Eq. (3)].

To demonstrate the noise-reduction capabilities of the proposed wavelength converter, we generated a modulated signal with noise added to the marks (1 bits) of both modulator outputs. Figure 3 shows 10-Gbit/s traces of the complimentary (noise-carrying) input signal at 1584 nm and the converted probe at 1491 nm under the condition of minimum walk-off. Since the complimentary data port monitors the input signal, the bit sequences of the input and the converted signals are identical. Histograms are added to highlight the changes in noise distributions. Both traces were recorded with the same average power at the receiver ($-16$ dBm), ensuring that they were equally affected by the receiver thermal noise.

The optical noise carried by a converted space (0 bit) is the compressed noise of an input mark. The detected output space contains shot and thermal noise contributions as well as beat noise that is due to optical noise. In the example shown in Fig. 3, the input mark contains a large noise level. Even though the optical noise is significantly amplified, it still dominates. An input space causes minor depletion and therefore has a small effect on the converted mark. However, the noise accompanying an input space, once it is amplified, may be large enough to have some influence on the noise of the converted mark. In the present case, Fig. 3, the noise is sufficiently small to ensure that the noise of the output mark is determined by the receiver thermal noise.

The noise suppression of the converter was modeled in two ways. First, we used perturbation analysis of cw signals to show that the standard deviation of the noise in the short-wavelength probe (assuming no noise at the input), $\sigma_{pr}$, is related to the standard deviation of the input noise in the long-wavelength signal, $\sigma_s$, by

$$\sigma_{pr} = P_p(0) \exp(-\alpha_{pr}L - C_R G P_{s,in} L_{eff}^s) C_R L_{eff}^s G \sigma_s,$$

where $P_{s,in}$ is the input signal power to the high-power L-band EDFA, whose gain is $G$ [i.e., $P_p(0) = G P_{s,in}$ is the power launched into the HNLF]. Equation (4) assumes zero walk-off between the two wavelengths and does not include noise enhancement introduced by modulation instability, which is present in practical situations.
Next, we simulated the cw noise transfer function, using the complete field propagation equations.\textsuperscript{5} The numerical results in Fig. 4 show the noise transfer ratio, $\sigma_{pr}/\sigma_s$, for several walk-off values as a function of the signal input power launched into the HNLF. To make a suitable comparison, we calculated $\sigma_{pr}$ and $\sigma_s$ for the same average power, and the probe signal was assumed to be noiseless at the input. As can be seen, $\sigma_{pr}$ is always smaller than $\sigma_s$ because of the induced depletion, but $\sigma_{pr}/\sigma_s$ is strongly dependent on power and walk-off. For the case of zero walk-off, the simulated noise is larger than that predicted by Eq. (4), since the simulation encompasses a noise enhancement that is induced by modulation instability.\textsuperscript{7} The introduction of walk-off between the two signals causes an averaging effect that reduces the noise transfer significantly,\textsuperscript{8} as can clearly be seen in Fig. 4.

Noise reduction due to intentional walk-off can be used only as long as it is small compared with the bit period, since large walk-off values reduce the ER and naturally impair complementary data mapping.

An important parameter is therefore the effective conversion bandwidth, defined as the spectral range allowing for a $Q$-factor enhancement while maintaining a large ER. Figure 5 shows calculated $Q$ factors and ERs at 10 Gbits/s as a function of the converted wavelength. In this simulation the signal wavelength was fixed at 1584 nm, with an input average power of $+21$ dBm and an initial $Q$ factor of 7.8 dB. The converted wavelength varied from 1470 to 1520 nm, and the output $Q$ factor and the ER were calculated for each wavelength. The predicted effective conversion bandwidth exceeds 35 nm for an output $Q$ factor larger than 10 dB. Furthermore, the ER exceeds 10 dB at each wavelength within the range. Note that the system does not exhibit symmetric behavior with respect to the zero-walk-off wavelength, located near 1491 nm, since the Raman gain varies and reaches a maximum near 1480 nm, where the ER is at its maximum value. In addition, a small walk-off with respect to the bit period enhances the reshaping performance by averaging the noise transfer between the signal and the probe, as illustrated in Fig. 4.

To conclude, we have proposed a novel Raman-mediated interband wavelength converter with reshaping and noise-reduction capabilities. We demonstrated wavelength conversion from the L to the S band at a bit rate of 10 Gbits/s, but the quasi-instantaneous Raman response makes the converter potentially useful for much higher bit rates. The main limiting factor of this converter is the walk-off effect, which we can reduce by decreasing the fiber length and increasing the fiber nonlinearity or by raising the optical power of the long-wavelength input signal.

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References