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Active tunable WDM demultiplexer with intrinsic gain based on vectorial parametric amplification

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We report on the realization of an active tunable wavelength division multiplexing (WDM) demultiplexer based on vectorial parametric amplification in a highly nonlinear bismuth-oxide fiber. The demultiplexing of a 10 Gbits/s WDM channel is demonstrated with little power penalty. The compact device integrates wavelength conversion and filtering functions while providing parametric gain. Furthermore, the proposed scheme could be extended to perform time division multiplexing (TDM) and WDM simultaneously.

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Introduction. To fill the speed gap between optical and electronic systems and obtain transparent optical communications, eliminating the need for optical–electrical–optical (O-E-O) conversion, all-optical signal processing has remained an active research area since the advent of optical communications, and many schemes and concepts have been introduced based on various underlying principles [1]. Among all possibilities, those based on four-wave mixing (FWM) and parametric interaction are specifically appealing, owing to the almost instantaneous response of this phenomenon, which makes it suitable for high-speed applications.

Fiber optical parametric amplifiers (FOPAs) are prolific devices, which have been demonstrated to accomplish a vast variety of useful functions, including signal regeneration, optical sampling, pulse generation, wavelength conversion, coherent detection, all-optical switching, and broadband amplification in both phase-insensitive and phase-sensitive modes [2–4]. In addition to the aforementioned applications, demultiplexing, which, in a broad sense, includes any ability to extract a signal multiplexed in time or wavelength directly in the optical domain, is another functionality that is of prime importance in the realization of transparent optical communication. Optical time division demultiplexing at very high speeds and with high efficiency based on parametric amplification has been reported [5,6]. These reports mostly date back to the time before the advent of wavelength division multiplexing (WDM) systems as the dominant technology.

The complex dependence of the gain profile of optical parametric amplifiers (OPAs) on pump power, P , and linear phase mismatch, $\Delta\beta$, leads to diverse shapes in attainable gain spectra. An interesting and beneficial gain profile can be obtained over a narrow region with tunable width and center wavelength [3]. This is achievable in two different situations: (i) when there is a negative fourth-order dispersion parameter, β_4 , together with normal and large dispersion; and (ii) when there is a large linear birefringence, $\Delta n = n_x - n_y$, where n_x and n_y are the refraction indices along the two principal axes of the fiber. In the latter case, amplification is mediated via vectorial parametric interaction between the pump and signal with a perpendicular state of polarization (SOP).

To obtain strong nonlinear interaction, some nonsilica fibers, such as highly nonlinear bismuth-oxide fibers (Bi-HNLFs), have recently been developed with extraordinarily large nonlinearity coefficients, γ , exceeding $1/(W\cdot m)$. However, some drawbacks in their characteristics, namely a very high fiber loss coefficient, α , of the order of 2 dB/m and a zero-dispersion wavelength (ZDW) falling in the spectral region of 2 μm and beyond, prevent them from being practically attractive for broadband parametric amplification. Nonetheless, some innovative applications could still be realized with these types of fiber.

In this paper, we report on the realization of the aforementioned exotic gain spectrum with narrow gain peaks, utilizing the birefringence of a Bi-HNLF in the CW operation regime; to our knowledge, this is the first time that this has been achieved. Furthermore, we exploit this gain spectrum in an innovative scheme to perform active optical demultiplexing in the wavelength domain. The proposed scheme is then utilized to demultiplex one out of three 10 Gbits/s WDM channels. It is worth emphasizing the point that the demultiplexed signal will not only not be attenuated, as in any other demultiplexing device, but will also experience gain. Furthermore, the proposed scheme could be extended straightforwardly to accomplish simultaneous time division multiplexing (TDM) and WDM. Full tunability over wavelengths and across channels adds to the value of the proposed scheme.

Operation principles. FWM is a polarization-dependent interaction, and its efficiency depends on the SOPs of the interacting waves. Normally, to obtain the maximum gain, the pump and signal are injected into an OPA with parallel SOPs, in which case the phase-matching condition is written as $\kappa = \Delta\beta + \Delta\beta_{NL}$, where $\Delta\beta = \beta_2\Delta\omega^2$, and $\Delta\beta_{NL} = 2\gamma P$ (for the single-pump case) can be interpreted as the nonlinear phase

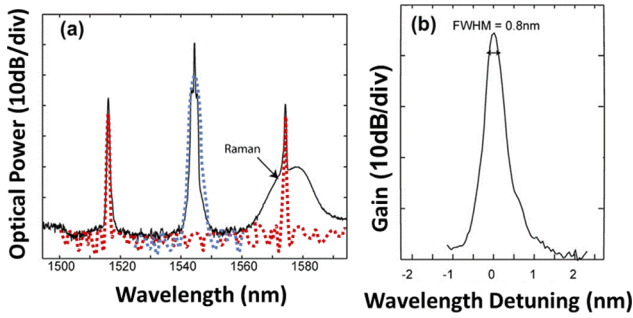


Fig. 1. (a) Experimental (black, solid) and simulation (dotted) graphs showing vectorial (red) and scalar (blue) amplified spontaneous emission (ASE) spectra. (b) Gain spectrum with ≈ 0.8 nm 3-dB bandwidth. Raman shift, ≈ 30 nm

mismatch. This expression needs modification in three ways, owing to loss, birefringence, and orthogonal SOPs of the pump and the signal, each aligned with one of the principal axes of the fiber, to read as

$$\kappa = \Delta\beta + \Delta n \frac{\omega_p}{c} - \frac{2}{3} \gamma P e^{-\alpha z} + i\alpha. \quad (1)$$

In addition, for orthogonal pump-signal SOPs, the maximum gain coefficient, g_{\max} , is reduced by a factor of 1/3 and equals $\gamma P/3$. Therefore, more pump power is required to obtain a reasonable gain in this condition.

In the fiber at our disposal, $\gamma = 2$ dB/m, $\beta_2 = 3 \times 10^{-25}$ s²/m, and $\Delta n = 1.9 \times 10^{-5}$; therefore, it could be verified that the first and second terms in Eq. (1) dominate. As a result, the width and position of the narrowband gain regions are independent of the pump power and are determined solely by the dispersion and birefringence parameters of the fiber. In fact, the term containing Δn is a constant term for a fixed pump wavelength and determines the relative distance of the gain regions from the pump; consequently, β_2 governs their width. Both parameters, i.e., Δn and β_2 , could be tailored over a wide range in the manufacturing process [7]; hence, both the position and the width of the gain regions could be tailored in accordance with the system requirements.

Using almost perfect rectangular pulses with 400 ps duration and a 1/64 duty cycle amplified up to 18 W peak power, we were able to observe the generation of vectorial modulational instability (MI) in the fiber, as shown in Fig. 1. As seen in the figure, simulations predict such gain regions perfectly correctly. The confirmation of the fact that the observed MI peaks originate from birefringence and not fourth-order dispersion comes from the fact that these peaks could be greatly reduced and even eliminated by slightly altering the SOP of the pump. It is also worth noting that scalar MI is also observable on the pedestal of the high-power pump over a nearly 10-nm region.

Since β_2 is positive and large, Δn must be negative, i.e., it is necessary to inject the pump on the slow axis of the fiber. We developed an elegant technique for finding these axes, based on stimulated Brillouin scattering (SBS) backreflection, as follows. SBS backreflected light power is maximized when the pump is aligned with either principal axis of birefringence. Therefore, using automated polarization controllers via the general purpose interface bus (GPIB) protocol, we swept the pump SOP over the whole Poincaré sphere and identified the two SOPs for which the counterpropagating power was maximal, as shown in Fig. 2(a).

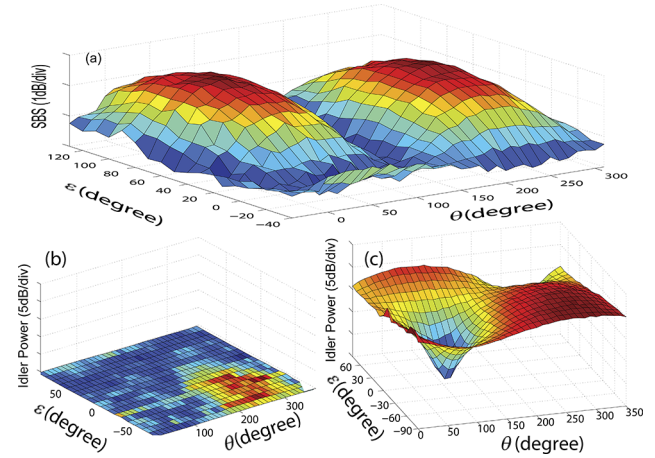


Fig. 2. (a) Backreflection due to SBS when SOP of pump sweeps Poincaré sphere: θ , azimuth angle; ϵ , altitude angle. Values of θ and ϵ are relative and have no absolute reference. Backreflection is clearly maximized at two points, corresponding to two principal axes of polarization. (b), (c) generated idler for signal SOP swept over Poincaré sphere, with pump on: (b) fast axis; (c) slow axis.

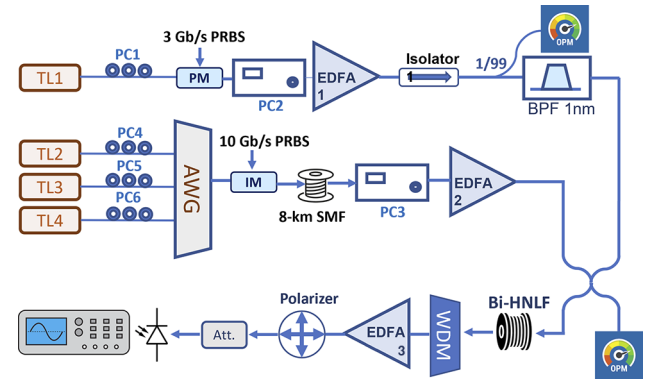


Fig. 3. Experimental setup: three tunable lasers (TL2, TL3, TL4) are modulated at 10 Gbits/s. Polarization controllers (PC2, PC3) are automated via GPIB protocol.

For each of these two SOPs, we then swept the signal SOP over the Poincaré sphere and inspected the generated idler power. Figures 2(b) and 2(c) show the two cases; in one case, no idler is observed, which obviously corresponds to the case in which the pump was on the fast axis; in the other case, the idler is generated and maximized. This determined the optimum signal SOP as well, which is controlled and maintained using the automated polarization controllers.

Experimental setup and results. The experimental configuration used for this experiment is shown in Fig. 3. A tunable laser (TL1) serves as the pump, which is phase-modulated with a $2^{31} - 1$ pseudorandom binary sequence (PRBS) RF input with 3-GHz frequency for SBS suppression purposes. It is then amplified with a high-power erbium-doped fiber amplifier (EDFA1) up to 4.5 W, and a tunable band-pass filter (BPF1) is used to remove the ASE of the EDFA. An isolator prevents any backreflections to the high-power EDFA. The SOP of the pump is controlled by a polarization controller (PC2). The pump is then injected into the HNLf through a 20-dB coupler. Since the splice between the coupler and the HNLf introduces a 2-dB loss, the power

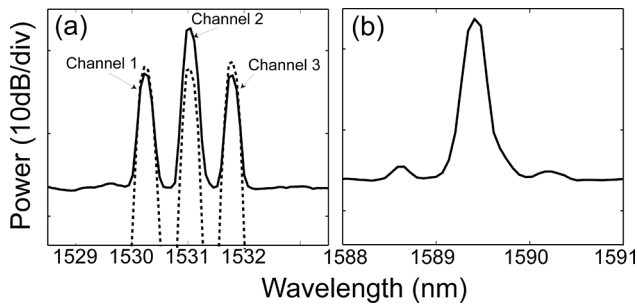


Fig. 4. (a) WDM spectra with pump on (solid) and off (dashed). The pump wavelength is adjusted at 1560.1 nm to amplify and filter channel 2. (b) Spectrum of generated idler for channel 2; cross talk is less than -20 dB.

injected into the Bi-HNLF was about 2.8 W. This is the highest CW pump power injected into such fibers, to our knowledge.

Three tunable lasers (TL2, TL3, TL4), with wavelengths $\lambda_1 = 1530.2$ nm, $\lambda_2 = 1531$ nm, and $\lambda_3 = 1531.8$ nm, are combined using an arrayed waveguide (AWG) and intensity-modulated at 10 Gbits/s. The signals are decorrelated by propagating them through an 8-km spool of single-mode fiber (SMF) and injected into the HNLF by the coupler after being amplified by EDFA2. The average power at the HNLF input was -12.3 dBm per channel. At the output, the pump is filtered out using a high-contrast polarizer. This is one of the advantages of this scheme: since the pump and the signal-idler pair are in perpendicular SOPs, the high-power pump could be effortlessly separated. Moreover, Raman-induced ASE, which is co-polarized with the pump, is also effectively eliminated by the polarizer.

The idler, filtered by the WDM coupler and amplified by EDFA3, is then directed to the receiver after appropriate attenuation. The spectra of the WDM signals are shown in Fig. 4(a) when the pump is on and off and its wavelength is adjusted at $\lambda_p = 1560.1$ nm. When the pump is on, channel 2 is amplified by about 10 dB, while the other two channels are slightly attenuated, owing to Raman loss. The cross talk, by which we mean the power ratio of the desired channel to the adjacent channel, is observed to be near -10 dB. Using alternating orthogonal polarization for adjacent WDM channels is a common approach to reduce cross-phase modulation (XPM) and FWM cross talk in practice; if such a technique is adopted, the cross talk of the neighboring channels would be negligible in the presence of the polarizer. Through parametric amplification, an idler wave is also generated at the symmetric wavelength with respect to the pump, and conveys identical data to the signal. It is seen in Fig. 4(b) that the demultiplexing of the idler is more effectual, as the cross talk is observed to be less than -20 dB. The generation of the idler could be advantageous, as it provides a degree of freedom in wavelength assignment for rerouting the signal. In fact, the proposed scheme is capable of integrating wavelength conversion and filtering functions. Moreover, the idler could be used as a phase-conjugated copy of the signal for the optical phase-conjugation technique in the mitigation of dispersion and deterministic nonlinear degradation. To assess the quality of the filtered signal, we measured the bit error rate (BER) for the filtered signals. The pump wavelength was adjusted to 1559.3 nm, 1560.1 nm, or 1561 nm to select channel 1, 2, or 3, respectively. Figure 5 shows eye diagrams recorded for the three channels. The eyes are clearly open and no considerable distortion is observed. The BER plots for the three channels are also depicted in Fig. 5,

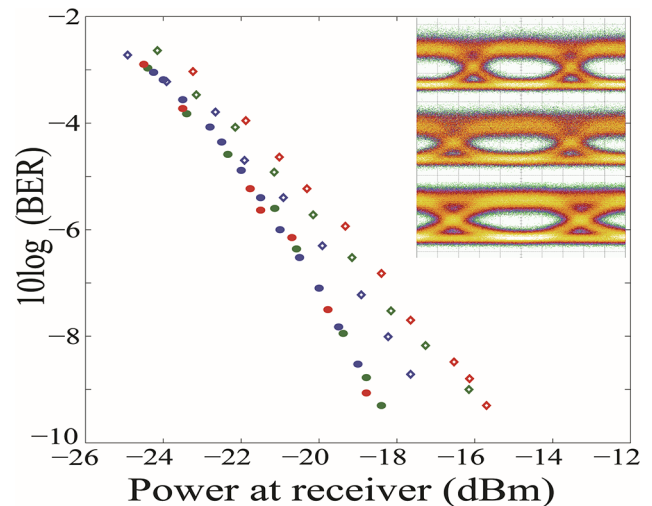


Fig. 5. BER for channels 1 (green), 2 (red), and 3 (blue) at idler wavelengths (diamonds), compared with back-to-back measurements at signal wavelengths (circles). Inset: Eye diagrams for three channels, respectively, from top to bottom.

for an input optical SNR (OSNR) of 24.5 dB. The operation of the demultiplexer with a low power penalty, less than 2 dB, is observed at BERs well below the forward error correction (FEC) limit. For example, while for channel 2, which exhibits the worst performance, the power penalty at $\text{BER} = 10^{-9}$ is slightly more than 2 dB, for channel 3 this penalty is below 1 dB. The difference in the performance of the three channels could be explained by considering the shape of the gain spectrum (Fig. 1), which exhibits a tail on the side toward the pump. As a result, channel 3, with no adjacent channel on its closest side to the pump, demonstrates the best performance. Obviously, the situation would be reversed if the signals were put on the other side of the pump.

An interesting way to extend the proposed scheme, with considerable practical importance, is to simultaneously demultiplex a time division multiplexed sub-channel out of the filtered WDM channel. It is realizable by using a pulsed pump instead of a CW pump where, by properly adjusting the pump wavelength, the main channel of interest in the WDM spectrum is filtered while the pump pulses are timed appropriately so that the pump and, consequently, the parametric gain are present only over the time period of the desired TDM sub-channel bits. Fig. 6 illustrates the operation principle. This is one of the rare situations in which an extra valuable functionality is simultaneously achieved with a number of other advantages. When using short pulses, the peak pump power could be very high, compared with the CW operation. In addition, since the pulsed pump already has a wide spectrum, no pump broadening is required to suppress the SBS backreflection. Therefore, using a pump with several watts of peak power, a high amount of gain is also provided to the signal, which adds considerably to the value of the proposed scheme. However, using pulsed pump OPAs for telecommunication applications introduces a great deal of difficulty. A pulsed pump essentially means varying pump power over the period of the pulse, which will modify the position and shape of the gain profile. This leads to inter-channel cross talk in the wavelength domain. However, this effect could be neglected, since, for an exponential gain regime, the pulse could be approximated with its peak power over the FWHM. Moreover, as mentioned before,

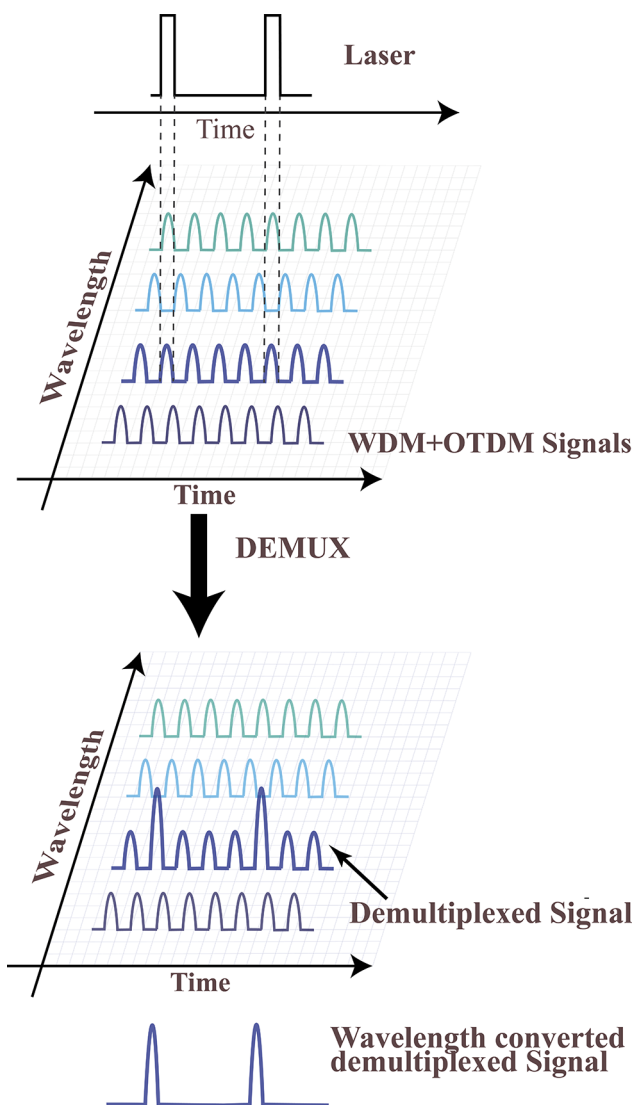


Fig. 6. Operation principle of simultaneous TDM-WDM demultiplexer based on vectorial parametric amplification. The pulsed pump is present over the desired TDM sub-channel, while its wavelength is such that the center of the gain region coincides with the desired WDM channel.

the Kerr effect and subsequent FWM have an instantaneous response. This means that parametric interaction could only take place for exactly spatially overlapping pulses; a condition that is impossible to maintain, owing to the walk-off between the pump and signal pulses, because of the inevitable dispersion. In addition, the exact temporal profile of the pump and signal pulses and the relative time delay between them will influence the shape of the output pulses. The modification of the pulses, particularly the pump pulse, owing to dispersion and self-phase modulation (SPM) adds to the complication as well. The combined effect of

all these issues is too complex to render the problem of determining the shape of the output pulses to analytic investigation or numerical simulation. However, one could find a quite thorough analysis in Hedekvist *et al.* [6], albeit with certain simplifying assumptions. At any rate, since the demultiplexing is normally performed at the end of the transmission link, as long as the output pulse has a well-defined temporal shape for sampling, the distortion of the pulses is not particularly important.

Conclusion. The possibility of creating narrowband parametric gain regions with a tunable center wavelength and bandwidth in CW mode, utilizing fiber birefringence for phase-matching, and with orthogonal pump and signal SOPs is experimentally demonstrated for the first time, to our knowledge. The presence of high fiber loss, orthogonal SOPs of the pump, and signal and birefringence of the fiber modify the phase-matching condition, as formulated in Eq. (1), which shows almost perfect consistency with the experimental result. The exotic gain regions are used in a proposed scheme for active WDM demultiplexing, and its feasibility is demonstrated experimentally by almost error-free demultiplexing of one out of three WDM channels. The scheme could be extended straightforwardly to simultaneous time-wavelength division demultiplexing; any TDM sub-channel from a WDM spectrum could be extracted. The fact that the demultiplexed channel would experience parametric gain instead of attenuation adds to the attractiveness of the scheme.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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