Polarization-Independent Wavelength Conversion at 2.5 Gb/s by Dual-Pump Four-Wave Mixing in a Strained Semiconductor Optical Amplifier

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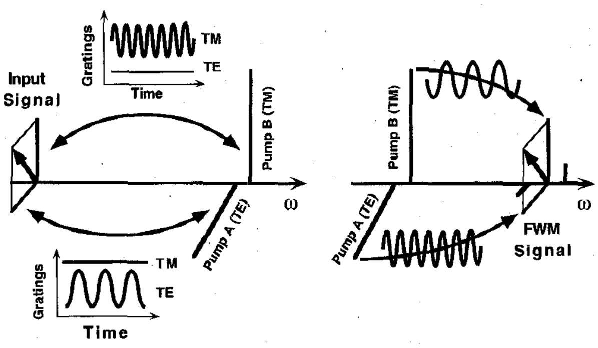
***Abstract*— We give a general expression for the polarization dependence of the four-wave mixing (FWM) efficiency in the dual-pump configuration. This expression, along with some general properties of the FWM susceptibility tensor, is used to propose a simple scheme to generate a nearly (1.5-dB variation) polarization independent FWM converted signal. The viability of this scheme is verified in a wavelength conversion experiment at 2.5 Gb/s.**



(a) (b)

Fig. 1. Polarization states of the waves for the polarization independent conversion. (a) The grating formation is shown; the beating of pump A and the TE component of the input signal generate a "slower" grating. Since pump A has no TM component, there is no probe polarization dependent interference effect in the generation of these gratings. Similarly, the TM component of the probe and pump B generate "faster" grating with no interference effects from TE waves. (b) Pump A scatters off the "faster" gratings into the TE component of the signal, and Pump B scatters off the "slower" gratings into the TM component of the signal. Also shown are the single-pump FWM signals (to the right and left side of the polarization independent signal). These come from the scattering of pump A off the "faster" gratings (left signal) and from the scattering of pump A off the "slower"gratings.

WAVELENGTH converters are essential devices to exploit the full fiber bandwidth in a wavelength division multiplexed network. Four-wave mixing (FWM) in semiconductor optical amplifiers (SOA) is a strong candidate to implement this function [1], [2]. Its intrinsic advantages include transparency to the modulation format and bit rate of the input signal, multiterahertz response bandwidth, small intrinsic chirp, ease and versatility of channel wavelength switching. In its usual single-pump configuration, the wavelength converted signal intensity strongly depends on the polarization state of the pump and the probe (input signal). Since most of the fiber used in telecommunication networks is not polarization maintaining, all system components should operate independently of the polarization of the signal waves. In general, there is no single-pump polarization setting which allows polarization independent FWM conversion [3]. In bulk amplifiers, Jopson [4] has demonstrated that any two orthogonal pump polarizations can be used in principle to obtain a wavelength conversion efficiency that is independent of the probe polarization. This is true for all isotropic media, and it has been demonstrated in a fiber four-wave mixing wavelength converter [5].

Strained quantum-well amplifiers have anisotropic active regions, and the FWM efficiency depends on the absolute and the relative polarizations of the pump and the probe. In general, the conversion efficiency from two orthogonal pumps will still depend on the probe polarization, and to achieve independence, the exact polarizations have to be calculated using conversion efficiency matrices. For the carrier density modulation and carrier heating FWM contributions considered in this letter, the single-pump converted signal can be expressed as a function of the pump and the probe via a 2×2 matrix [3]. In the dual-pump configuration, the converted signal of interest can be described in terms of two such matrices, one corresponding to the conversion efficiency at the detuning between the signal and the first pump, and other for the detuning with the second pump. Thus, in general, to compute the polarization state of the two pumps for which the conversion efficiency is exactly independent of the probe polarization, eight conversion parameters must be known for each wavelength configuration.

In this letter, we present an approach using alternating-strain quantum-well SOA's [6], for which there is a simple pump configuration yielding nearly-polarization independent wavelength conversion. No material parameters need to be determined, and the method can be applied for almost any wavelength shift, anywhere within the gain spectrum of the amplifier. We demonstrate the feasbility of this scheme in a wavelength conversion system, at 2.5 Gb/s.

Two processes are responsible for the FWM conversion in a SOA. First, the beating of the input waves generate dynamic

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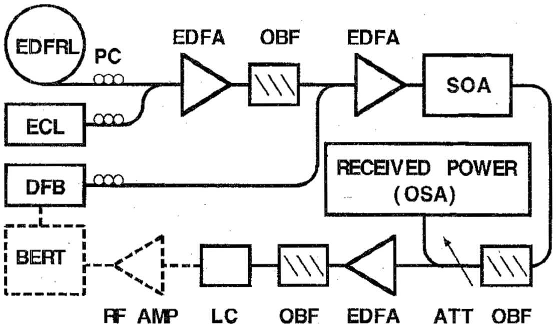

Fig. 2. Schematic view of the experimental setup. The acronyms are EDFRL: erbium-doped fiber-ring laser, ECL: external cavity laser, DFB: distibuted feedback laser, PC: polarization controller, OBF: optical bandpass filter (optical bandwidth: 1 nm FWHM), EDFA: erbium-doped fiber amplifier, SOA: semiconductor optical amplifier, ATT: variable attenuator, OSA: optical spectrum analyzer, LC: lightwave converter, RF AMP: 3-GHz electrical amplifier, BERT: bit-error rate tester (including signal generator and microwave transition analyzer). Dashed lines refer to electrical signals.

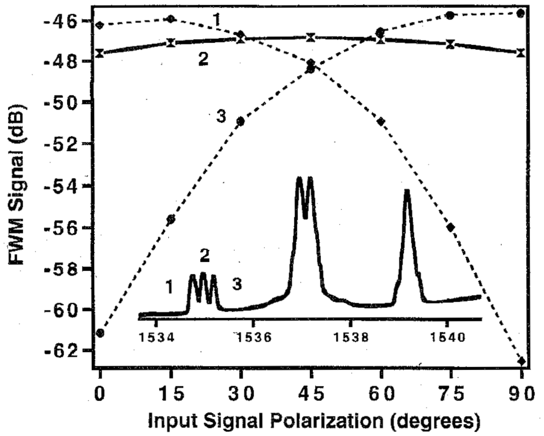

Fig. 3. FWM signals for various linear input signal polarizations: the solid line is the dual-pump signal while the two dashed lines are the adjacent single-pump FWM products. The inset shows the spectrum at the output of the SOA with the signal polarization at 45°. 2 dB on the vertical scale correspond to 20 dB on the inset. Angles are measured relative to the quantum-well growth axis.

gain and index gratings, and then these same waves scatter from these gratings into the four-wave mixing sidebands. Two "types" of dynamic gratings are formed, one through beating of the TE components of the input waves, the other through beating of their TM components. The TE (TM) component of the converted signals is generated by scattering of the TE (TM) components of the pumps off *both* types of gratings. The polarization dependence of the FWM efficiency results from the interference between these contributions [3]. The FWM process of interest in the dual-pump configuration is one in which the grating formation and the scattering processes involve different pumps. The amplitude of the wavelength converted signal at the output of the amplifier is given by

$$E_i^s(L) = \sum_{k=1}^{2} E_i^A M_{ik}^{AB} E_k^B \left(E_k^q\right)^* + E_i^B M_{ik}^{BA} E_k^A \left(E_k^q\right)^* \quad (1)$$

where $\vec{E}^A$, $\vec{E}^B$, and $\vec{E}^q$ are the complex field amplitudes of the pumps and the signal at the input of the SOA, and the subscripts $i, j = 1, 2$ refer to their components along TE, TM direction. M_{ij}^{AB} is the short-hand notation for a 4th rank tensor M_{ijkl} subject to the selection rules $i = j$, $k = l$ [3]. The superscript AB means that the pump A is scattered into the converted signal and the gratings are generated with pump B. These tensor elements are the product of the FWM susceptibility tensor times a factor to account for the propagation of the waves through the waveguide.

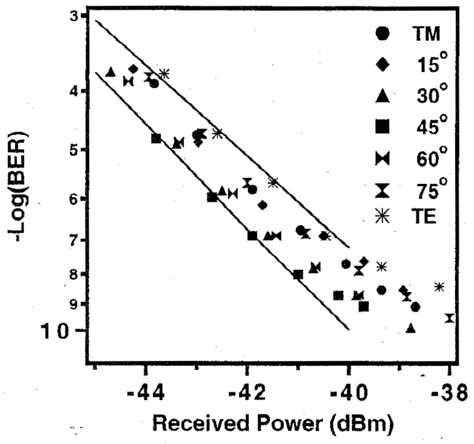

Fig. 4. BER versus received power for 6-nm wavelength shift at 2.5 Gb/s, for a $2^7 - 1$ pseudorandom data stream. The received power was measured on the OSA with a 0.5-nm detection bandwidth.

TABLE I
POLARIZATION SENSITIVITY OF THE CONVERTED SIGNAL FOR VARIOUS SETS OF ORTHOGONAL PUMP POLARIZATIONS

Pump A	Pump B	Max/Min FWM signal
+45	-45	2.8 dB
+60	-30	3.5 dB
σ_+	σ_-	2.9 dB
TE	TM	1.5 dB

To compare our results with the case of isotropic conversion media (i.e., bulk active layers), we also checked the absolute polarization dependence of the mixing for various sets of orthogonal pump polarizations. The results are shown in Table I. We noticed that for the alternating-strain device tested, changes in the absolute polarization of the two pumps does not affect the polarization dependence of the efficiency too much. This is a result of the weak anisotropy of these devices, and is not to be expected for, say, a highly-tensile strained quantum-well amplifier.

Given M^{AB} and M^{BA}, one can use (1) to compute the polarization states for the two pumps for which the conversion is independent of the probe polarization. The simpler approach considered here consists of reducing the contributions to each signal component to one (the main polarization dependence stems from the interference between the terms contributing to each component of the signal). This is done by setting one pump along TE and the other along TM, as shown schematically in Fig. 1. Nearly polarization-independent wavelength conversion is then obtained because of two properties of the M matrices. One is that in the limit where the detuning between the pumps is much smaller than that between the pumps and the probe $M^{AB} \sim M^{BA}$. In that limit, the detuning between the input signal and the two pumps is almost the same, thus the gratings are generated with the almost the same efficiency. The second property is that the alternating-strain devices used in our experiment have nearly equal off-diagonal components $M_{12} \sim M_{21}$[1] (a result of carefully engineered bandgap structures with low-gain anisotropy [7]).

Practically, the choice of the detuning between the two pumps is critical. Very small detunings require narrow bandpass filters to separate the polarization independent FWM signal from the adjacent single-pump FWM signals which are strongly polarization dependent.[2] On the other hand wider detunings, on the order of the detuning with the signal, will no longer yield a polarization independent signal.

The experimental setup used to verify this polarization independent conversion scheme is shown in Fig. 2. An external cavity laser and an Er-doped fiber ring laser were used as pumps. Their spacing was 0.2 nm. After preamplification, they were combined with the signal from a directly modulated DFB laser (digital laser module, from Ortel Corp.). The three lasers were amplified to a total power of about +19 dBm and coupled into the SOA. The polarization states were adjusted by inserting a polarizer at the input of the amplifier and then monitoring the power on a spectrum analyzer placed after the SOA. To detect the modulated signal, we used two bandpass filters to single out the polarization independent signal, one before and one after the optical preamplifier. The electrical signal was detected with an HP 11982 A lightwave converter, and amplified with a 3 Gb/s RF amplifier (HP 8347 A). The signal generator, microwave transition analyzer and bit error rate tester used in the experiment were models HP 70340, HP 70820, and HP 70843, respectively.

The inset to Fig. 3 shows the spectrum at the output of the SOA for a wavelength shift of 6 nm with the probe linearly polarized at 45° relative to the growth axis. The data plotted in Fig. 3 give the polarization dependence of the of the three distinct products (i.e., 1, 2, 3) that result from FWM. The variation of the central FWM peak (labeled 2 in the figure) is less than 1.5 dB for all possible linear polarizations of the input signal. This remains the case for random elliptical polarizations of the input signal as well. The residual polarization dependence is consistent with the relative values of M_{12} and M_{21} measured on a similar device [3].

Fig. 4 shows the BER vs. received power for the same set of input signal polarizations. The best results are obtained for a signal at 45°, but the penalty to the worst case (TE here) is less than 1.7 dB. The exact location of the bandpass filters is important; if they are not exactly on the center peak (peak 2), some of the polarization dependent single-pump FWM will be detected. We found that this can be used to compensate for the slight asymmetry in the M tensor, and by optimum filter placement the penalty could be further reduced to 1.3 dB. The straight lines in Fig. 4 are linear fits to the error rate data, where only the points above 10^{-8} were taken. The floor that appears for lower error rates is still under investigation. We repeated the experiment at different detunings, and even for the lowest signal shift (4 nm), there was no measurable increase of the polarization dependence with 0.2 nm pump detuning.

In conclusion, we have given a general expression for the polarization dependence of the FWM efficiency in the dual-pump configuration. In view of the complications involved in the generation of a strictly polarization independent FWM signal, we propose a simplified configuration which yields a nearly polarization independent conversion efficiency. We have experientally confirmed the viability of this scheme, by measuring a BER penalty of less than 1.7 dB at transmission rates of 2.5 Gb/s.

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[1] We note that interwell coupling is negligible at the detuning frequency studied in this work [6]. As a result, the nonlinearity contributing to the polarization independent signal is deried entirely from the tensile wells. However, the compressive wells are required to maintain $M_{12} \sim M_{21}$.

[2] Ultimately, of course, the minimal detuning will be set by the data bandwidth, since below that the beatnote between the pumps will interfere with the data in the converted signal.