Interchannel cross talk caused by pump depletion in periodically poled $LiNbO_3$ waveguide wavelength converters

Roey Harel*, William H. Burkett†, Gadi Lenz, and Edward E. Chaban

Bell Laboratories, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Krishnan R. Parameswaran and M. Martin Fejer

E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4085

Igal Brener

Tellium, Inc., 2 Crescent Place, Oceanport, New Jersey 07757

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We study experimentally and theoretically the limits of multichannel parametric wavelength conversion imposed by pump depletion in periodically poled $LiNbO_3$ waveguides. As many as 55 channels with 6 dBm of power each can be converted simultaneously with less than a 10^{-9} error rate by use of 20 dBm of pump power.

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1. INTRODUCTION

All-optical parametric wavelength converters are emerging as key components in all-optical transparent networks because of their modulation format transparency and bit-rate independence. There are various choices for parametric wavelength converters; they include nonlinear fibers, semiconductor optical amplifiers, and nonlinear waveguides.[1] In the last-named category, one of the most efficient and practical wavelength-conversion devices is based on cascaded $\chi^{(2)}$ processes in periodically poled $LiNbO_3$ (PPLN).[2–4] In these devices a pump at frequency ω_{Pump} is doubled to $2\omega_{\mathrm{Pump}}$ by means of second-order nonlinearity $\chi^{(2)}$ through second-harmonic generation. Simultaneously, difference-frequency generation between the doubled pump at $2\omega_{\mathrm{Pump}}$ and multiple data channels at ω_i ($i = 1,2,\ldots n$) produces multiple converted channels at $2\omega_{\mathrm{Pump}} - \omega_i$. The generation of wavelength-shifted channels and the parametric gain that occurs in the original data channels result in depletion of the frequency-doubled pump. This effect limits the maximum power in all the combined wavelength-division multiplexing (WDM) channels, or, alternatively, the number of WDM channels that can be simultaneously converted for given channel and pump powers.

In this paper we present a quantitative study of the pump depletion effect on wavelength conversion efficiency and on channel bit-error rate (BER). In a WDM system, pump depletion decreases the optical power of a tested channel. This effect, because of the existence of multiple channels, increases the BER of the tested channel and demonstrates interchannel cross talk among all the WDM channels. This study is important not only for wavelength conversion but also for multichannel phase conjugation.[5]

2. DEVICE CHARACTERISTICS AND EXPERIMENTAL SETUP

The waveguides were fabricated by annealed proton exchange in PPLN.[6] The device used in this experiment is 6 cm long, has a quasi-phase-matched period of 14.75 μm and a waveguide width of 12 μm, and was made by use of an initial proton exchange depth of 0.71 μm followed by 26 h of annealing at 327.5 °C. These parameters permit second-harmonic phase matching between the fundamental transverse waveguide mode of the pump at 1552.8 nm and the second-harmonic at 776.4 nm as well as phase matching of the near-degenerate DFG process (at $T = 120\,°\mathrm{C}$).

Figure 1 presents a schematic description of the experimental setup. The pump ($\lambda_P = 1552.84$ nm) is an external-cavity laser (ECL) amplified by a high-power erbium-doped fiber amplifier (EDFA) to a level of ~20 dBm and filtered to suppress the amplified spontaneous emission. This pump is multiplexed with signals generated by two additional ECLs by use of a WDM coupler. One of them (ECL1) serves as a data channel ($\lambda_S = 1542.34$ nm), and it is modulated by a Mach–Zehnder interferometer (MZI) at a bit rate of 10 Gbits/s (pseudorandom binary sequence word length, $2^{31} - 1$). The other laser (ECL2) serves as a source for pump depletion ($\lambda_{\mathrm{Dep}} = 1543.48$ nm), and it is modulated by another MZI at a slow frequency (10 kHz) with a duty cycle of 1:100. The modulated light from the latter MZI is amplified by another erbium-doped fiber amplifier and passed through a bandpass filter and a variable attenuator. This setup allows us to produce variable-power pulses with a maximum peak power higher than the average pump power. This laser is used to simulate a variable number of extra data channels with equal power propagating through the $LiNbO_3$ waveguide. We assume that all those channels are polarized along the z direction (perpendicular to the waveguide surface). The justification for using a single laser to simulate multiple WDM channels is based on the uniformity of the phase-matching properties for parametric processes in $LiNbO_3$. In Ref. 2 it was shown that the wavelength conversion efficiency is constant for a bandwidth of ~70 nm.

We launched the three lasers into the waveguide, and we filter the exiting light to measure only the frequency-converted data channel (from ECL1). This was then detected and analyzed by an optically preamplified receiver and a BER tester (BERT, Fig. 1). The BER tester was effectively triggered by the 10-kHz signal driving the second modulator (of ECL2). The fiber-to-fiber coupling loss in this configuration was measured to be ~6 dB as a result of reflection losses and mode mismatch between the fibers and the waveguide at the uncoated facets (~2.0 dB at each facet) and of intrinsic waveguide losses (~2.1 dB, i.e., ~0.35 dB/cm).

3. EXPERIMENTAL RESULTS

Figure 2 shows the measured BER for the converted channel (at $\lambda_{\mathrm{Conv}} = 1563.52$ nm) and for $P_{\mathrm{Dep}} = 0$ mW. As can be seen, a BER smaller than 10^{-9} can be achieved for receiver powers higher than -31.6 dBm. The inset shows the measured optical spectrum in the presence of P_{Dep}. Both the data channel (λ_S) and the cw channel (λ_{Dep}) are spectrally inverted. The conversion efficiency for the data channel is approximately -10 dB for a pump power of $P_{\mathrm{Pump}} = 20$ dBm.

Figure 3 shows the measured BER (filled squares) as a function of P_{Dep} for the converted data channel (λ_{Conv}). The pump power is kept constant at $P_{\mathrm{Pump}} = 20$ dBm. The BER remains below 10^{-11} for $P_{\mathrm{Dep}} \leq 10$ dBm. As P_{Dep} increases, the measured BER increases rapidly and approaches a value of 10^{-3} at $P_{\mathrm{Dep}} \approx 27$ dBm.

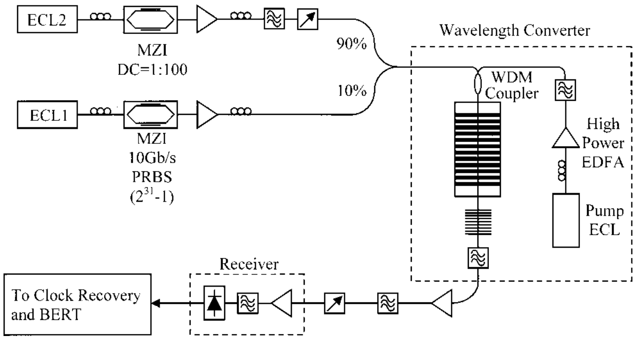

Fig. 1. Schematic diagram of the experimental setup: ECL1 represents the tested channel; ECL2 represents additional multiple WDM channels. Both lasers go through a polarization controller before entering the modulators. PRBS, pseudorandom binary sequence; DC, duty cycle; BERT, BER tester.

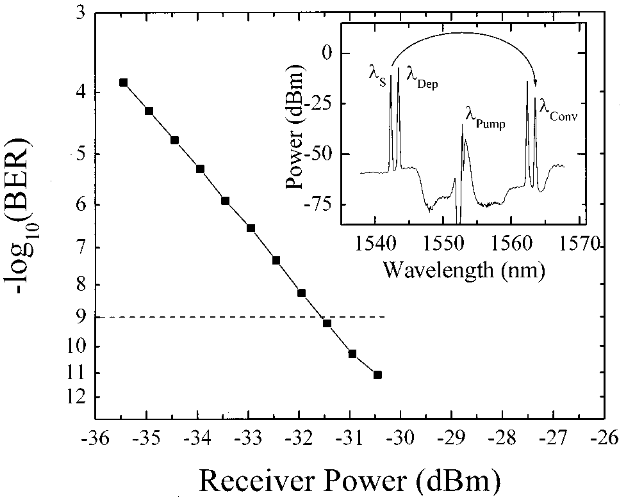

Fig. 2. Measured BER of the converted channel at $\lambda_{\mathrm{Conv}} = 1563.52$ nm when $P_{\mathrm{Dep}} = 0$ mW. Inset, measured optical spectrum in the presence of P_{Dep}.

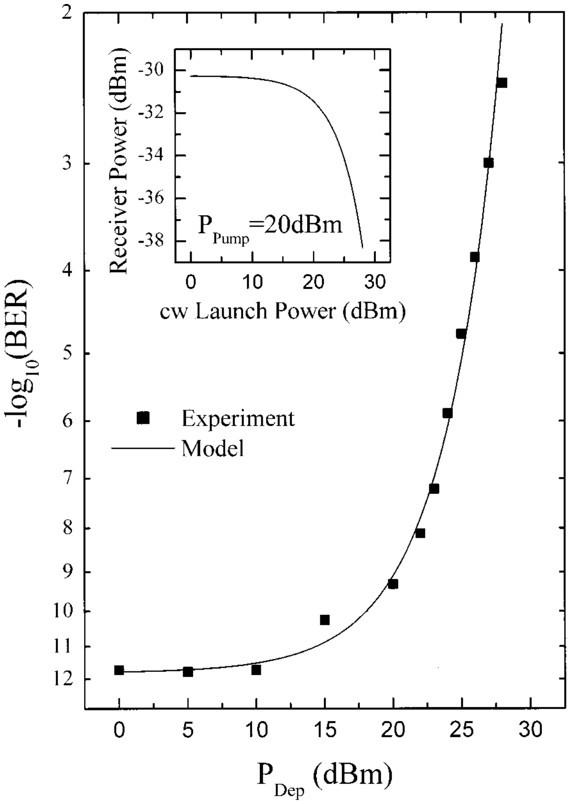

Fig. 3. Measured BER (filled squares) and calculated BER (solid curve) as a function of P_{Dep}. Inset, calculated P_{Conv} as a function of P_{Dep}.

4. MODEL

The experimental results can be understood as follows: P_{Dep} models multiple data channels, each with a power I_0, which would be present in a real WDM system. For low P_{Dep} (a small number of low-power channels), the depletion of the frequency-doubled pump is negligible, and the conversion efficiency of the channel of interest does not depend on the total number of channels in the system. When P_{Dep} is increased (many low-power channels), the frequency-doubled pump experiences depletion and the converted signal decreases, leading to a reduced signal-to-noise ratio and a higher BER. This effect depends on the pump power and on the total number of channels in the system.

We analyzed these results by solving a set of six coupled nonlinear wave equations that represent the various waves interacting in the PPLN waveguide. Note that all pump depletion effects and waveguide losses are included in this model. Fiber-to-fiber coupling losses were also taken into consideration in the calculation.

We calculated the dependence of the converted data channel power, P_{Conv}, on P_{Dep} (shown in the inset of Fig. 3). The model clearly shows the effect of pump depletion as a reduction in the converted channel power (and, hence, in the conversion efficiency) as P_{Dep} increases. The reduction in the conversion efficiency resulted in an increased BER. Using the measured BER (Fig. 2), we associated with each value of the calculated P_{Conv} (Fig. 3, inset), a corresponding BER and plotted its dependence on P_{Dep} (Fig. 3, solid curve). The calculation and the measured results are in excellent agreement.

To predict the total number of channels that can be simultaneously converted without encountering BER degradation, we analyze the results obtained from the model in conjunction with a statistical model. In a transmission system with $N + 1$ channels, each one of which has a random pattern, the pump depletion depends on the total power in all channels. The BER for a specific channel (the tested channel) depends on the bit pattern in the other N channels. In other words, the other N channels deplete the pump by different amounts, depending on whether their current bit is a 0 or a 1, with the result that different errors are experienced by the tested channel. Therefore we find the predicted BER_N experienced by the tested channel for an optical network with $N + 1$ channels by summing over all possible combinations of bits in the other N channels, and it is represented by

$$\mathrm{BER}_N = \frac{1}{2}\sum_{k=0}^{N}\frac{1}{2^N}\,\frac{N!}{k!(N-k)!}\,\mathrm{BER}(P_{\mathrm{Dep}} = kI_0).$$

Each term inside the summation is a product of two elements: (a) the probability of having a combination of k bits of 1 and $(N - k)$ bits of 0 and (b) the BER that the tested channel will experience for that combination.

We calculated this effect as a function of the number of WDM channels, assuming 6 dBm of power per channel. Figure 4(a) shows the predicted BER experienced by a tested channel as a function of the number of neighboring channels. It is clear that a BER of $<10^{-9}$ can be achieved for a channel count of <55. Figure 4(b) shows the power penalty experienced by the tested channel as a function of the number of neighboring channels. The tested channel experiences a power penalty below 1.2 dB for WDM system with a channel count of less than 55.

In conclusion, we have demonstrated experimentally and numerically that pump depletion in PPLN waveguides is the source of interchannel cross talk. We found that simultaneous multiple-channel wavelength conversion is not negatively affected by interchannel cross talk in systems in which the number of channels is <55 and when the power per channel does not exceed 6 dBm and for a pump power of 20 dBm. We found that under these conditions the power penalty is less than 1.2 dB.

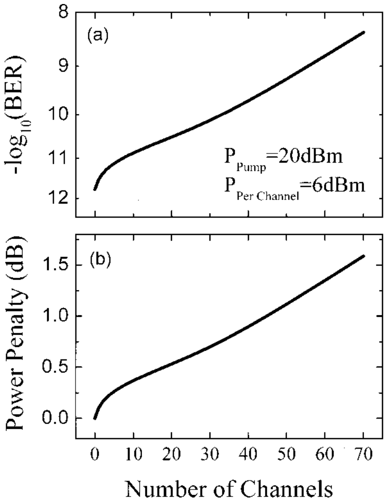

Fig. 4. (a) Predicted BER and (b) the power penalty of a tested channel as a function of the total number of additional channels in the optical network.

*Present address, Tellium, Inc., 2 Crescent Place, Oceanport, New Jersey 07757; e-mail address: rharel@tellium.com.

[†] Also at Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701.

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