179

IEICE TRANSACTIONS

on Electronics

VOL.E83-C
NO.6
JUNE 2000

A PUBLICATION OF THE ELECTRONICS SOCIETY

The Institute of Electronics, Information and Communication Engineers
Kikai-Shinko-Kaikan Bldg., 5-8, Shibakoen 3chome, Minato-ku, TOKYO, 105 JAPAN

INVITED PAPER *Special Issue on Advanced Optical Devices for Next Generation Photonic Networks*

Optical Signal Processing and Switching with Second-Order Nonlinearities in Waveguides

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SUMMARY We present three-wave mixing devices useful for signal processing functions in WDM and TDM systems, including wavelength conversion, spectral inversion, and gated mixing. These mixers exhibit extremely wide bandwidth, low noise, high efficiency, and format transparency.

key words: *three-wave mixing, optical signal processing, optical switching, wavelength conversion, lithium niobate*

1. Introduction

A number of techniques have been used in recent years to implement all-optical functions such as wavelength conversion for WDM systems, gated mixing for TDM multiplexing and demultiplexing, spectral inversion for dispersion compensation, and optical switching. Among these, three-wave mixing in $\chi^{(2)}$ media, which otherwise could be applied to all of these functions with an attractive combination of wide bandwidth, format transparency, and negligible degradation of signal to noise ratio [1], has not been widely exploited due to several technical issues, including high passive insertion loss, low mixing efficiency, and polarization sensitivity. In this paper, we describe devices fabricated with techniques that avoid these issues in both three-wave-mixing and cascaded three-wave-mixing configurations [2] based on periodically-poled lithium niobate (PPLN) waveguides. Experiments using these devices in wavelength conversion, spectral inversion, dispersion compensation by mid-span spectral inversion (MSSI) in a WDM transmission system, and all-optical gating are presented.

2. Theory

In a difference frequency mixer, inputs at frequencies ω_p and ω_s generate an output at frequency $\omega_{out} = \omega_p - \omega_s$. The output power P_{out} of such a mixer is related to the pump power P_p and the signal power P_s by $P_{out} = \eta P_p P_s$, where $\eta[\mathrm{W}^{-1}]$ is the nonlinear efficiency, proportional to the square of the length of the device and to the overlap of the pump, signal, and output modes. The best devices operating around 1.5 μm wavelengths today have normalized efficiencies around 0.5–1 $\mathrm{W}^{-1}\mathrm{cm}^{-2}$, so that in 5 cm long devices efficiencies on the order of 10 W^{-1} are obtained. Note that for a fixed pump power of about 16 dBm, such a device has an output linear in the signal power, with conversion loss of 3 dB. For communications applications, operation is typically near degeneracy, i.e. the signal and output wavelengths are in the 1.5 μm band, and the pump is around 0.78 μm. For an input frequency $\omega_s = \omega_p/2 + \Delta$, the output frequency is $\omega_p/2 - \Delta$, that is the output spectrum is the input spectrum mirrored around half the pump frequency (Fig. 1(a)). The output electric field E_{out} is proportional to the complex conjugate of the signal field, E_s^*, so the device also operates as a phase conjugator or spectral inverter.

The cascaded configuration, where second harmonic generation of the pump occurs simultaneously with the difference mixing process, is advantageous in situations where it is more convenient to operate with a pump in the 1.5 μm band. With two sequential $\chi^{(2)}$ processes, these devices require several dB more pump power than is typically required for a simple difference frequency mixing device. Viewed as a black box, with

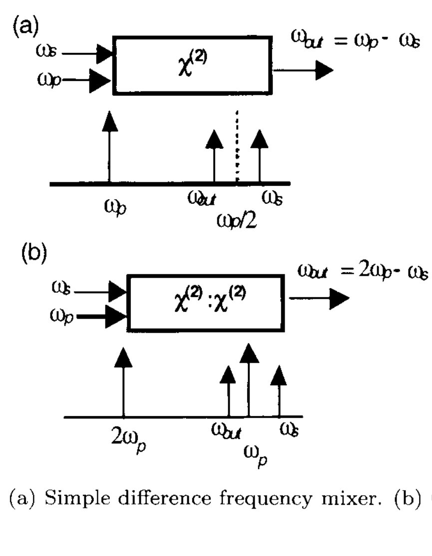

Fig. 1 (a) Simple difference frequency mixer. (b) Cascaded mixer.

Manuscript received December 24, 1999.

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$\omega_{out} = 2\omega_p - \omega_s$, these cascaded devices operate similarly to conventional FWM interactions, but with a much larger effective $\chi^{(3)}$ (a 5 cm PPLN waveguide has efficiency comparable to several km of dispersion shifted single-mode fiber), and without parasitics such as SBS and undesired FWM interactions that interfere with typical FWM devices.

3. Difference Frequency Mixing Experiments

All the devices in our studies are fabricated in annealed proton-exchanged (APE) lithium niobate waveguides. Quasi-phasematching (QPM) was accomplished with periodic electric-field poling, as described in [3]. Typical devices were 4–5 cm long, with QPM periods of 14.7 μm. Insertion losses were minimized through use of adiabatically tapered waveguides to separately optimize input coupling and mixing regions [4]. Passive fiber-to-fiber losses of 3 dB were obtained, along with nonlinear efficiencies of 5–10 W^{-1}. Near degeneracy, where signal and output propagation constants tune in an equal and opposite fashion (for a fixed pump frequency), the bandwidth depends only on the square root of the length of the device. Hence it is large even with devices as long as 5 cm, for which 3 dB bandwidths of 60 nm are obtained (Fig. 2). In this device operating in the 1.5 μm band with 90 mW of pump power at 0.78 μm, the conversion loss was 4 dB [3]. As the only noise source is parametric fluorescence, and the only saturation mechanism is gain compression due to pump depletion, these devices have a large dynamic range. Operation at low enough power to avoid gain compression and high enough to avoid degradation of signal to noise ratio is generally easy to achieve. We have observed a 50 dB linear dynamic range, from −54 dBm to −4 dBm, limited by measurement equipment rather than the mixing device itself (Fig. 3).

Another advantage of three-wave mixers is their ability to convert symmetrically from the 1.3 μm band to the 1.5 μm band and from 1.5 μm to 1.3 μm. Devices designed for this purpose show conversion loss of 9 dB with 40 mW pump power (Fig. 4 [5]).

The absence of undesired FWM mixing products allows simultaneous conversion of multiple input channels without interference. Operation of a cascaded device with four signal channels at 200 GHz spacing [4] is shown in Fig. 5. In this case the pump at 1547 nm is

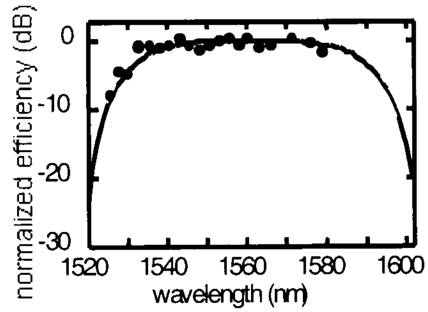

Fig. 2 Efficiency vs. signal wavelength for a fixed pump wavelength in basic difference frequency mixer.

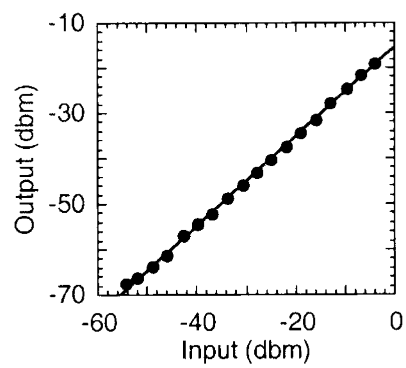

Fig. 3 Mixed output power vs. input signal power for fixed pump power.

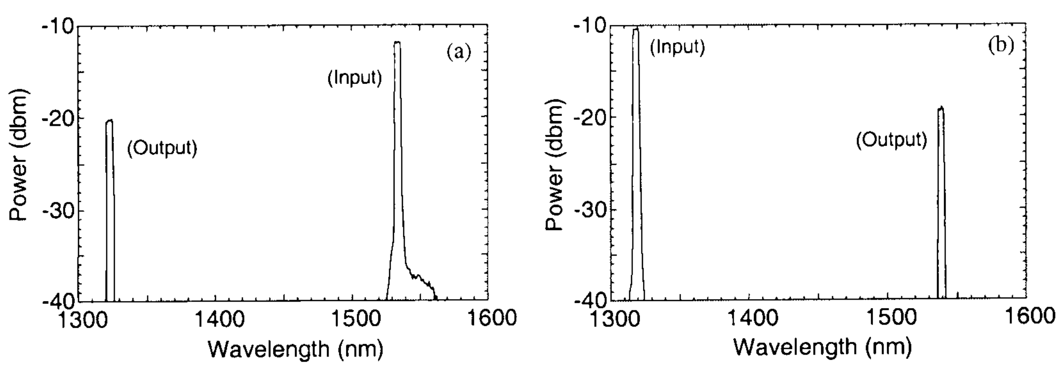

Fig. 4 (a) Measured optical spectrum for a signal at 1533 nm and its converted output at 1324 nm. The conversion efficiency is −9 dB with 40 mW pump power, corresponding to a nonlinear mixing efficiency of 380%/W. (After correction for waveguide propagation losses and Fresnel losses) (b) Optical spectrum for a signal at 1319 nm and its converted output at 1538 nm.

obtained by amplifying an ECL in an EDFA. The external (fiber to fiber) efficiency was −13.5 dB for 100 mW pump power, and rises to −7 dB for 200 mW pump power. About 1.5 dB of signal parametric gain is observed at this pump power level.

4. Mid-Span Spectral Inversion

This same device was used successfully in a demonstration of mid-span spectral inversion (MSSI), where dispersion compensation of four 10 Gb/s WDM channels at 200 GHz spacing over a 150 km link was achieved [6]. The setup is shown in Fig. 6, with resulting eye diagrams and BER curves in Figs. 7 and 8 respectively. The received eye, clearly closed by dispersion in the fiber link, is reopened when the MSSI device is used, with minimal power penalty resulting from the conversion process.

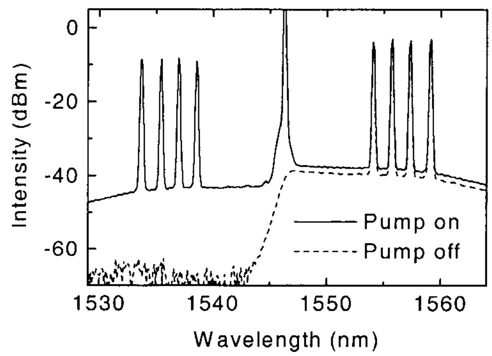

Fig. 5 Spectrum of input signal and converted output with and without pump. The input channels are at the long wavelength side of the 1547 nm pump peak.

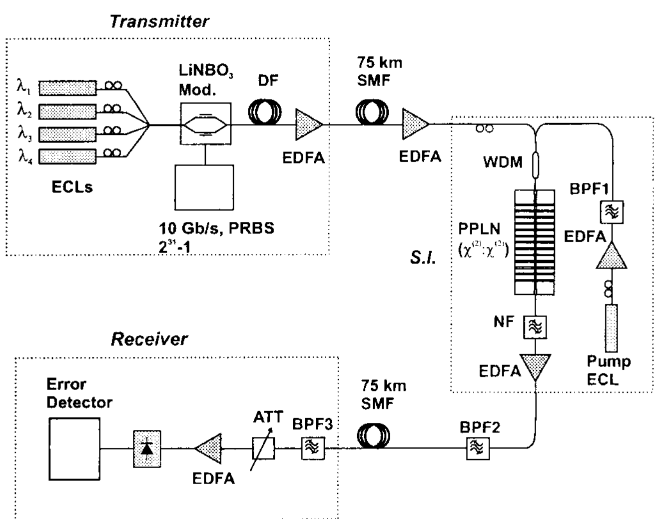

Fig. 6 Experimental setup used to demonstrate the performance of the PPLN waveguide spectral inverter. NF: notch filter; BPF: bandpass filter; DF: decorrelation fiber.

5. Polarization Diversity

The intrinsic single-polarization nature of QPM devices in APE $LiNbO_3$ is a key impediment for practical applications. Polarization diversity solutions such as those shown in Fig. 9 can be implemented to address this issue. Figure 9(a) shows one configuration where two waveguides on the same chip are used, one for each polarization [7]. One difficulty with this configuration is that the two waveguides must be identical in order to have equal conversion efficiency. A second problem is that a delay line is needed in one of the arms in order to compensate for any path length difference.

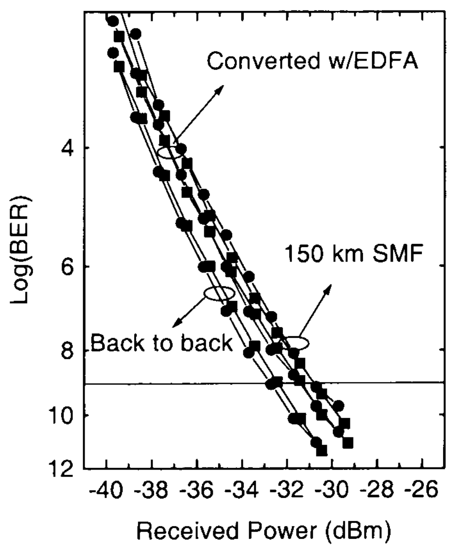

Fig. 8 BER curves for the two center channels: back to back; after conversion in the MSSI device and amplification by one EDFA (no fiber); after MSSI and transmission through the full 150 km of SMF.

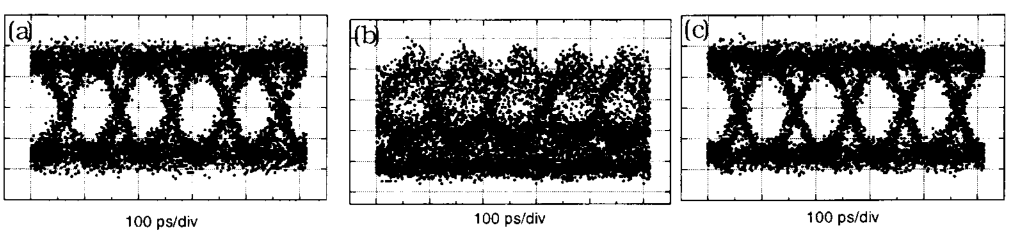

Fig. 7 Eye diagrams for one of the channels (a) back to back; (b) unconverted after 150 km of SMF; (c) after MSSI by our device and 150 km of SMF.

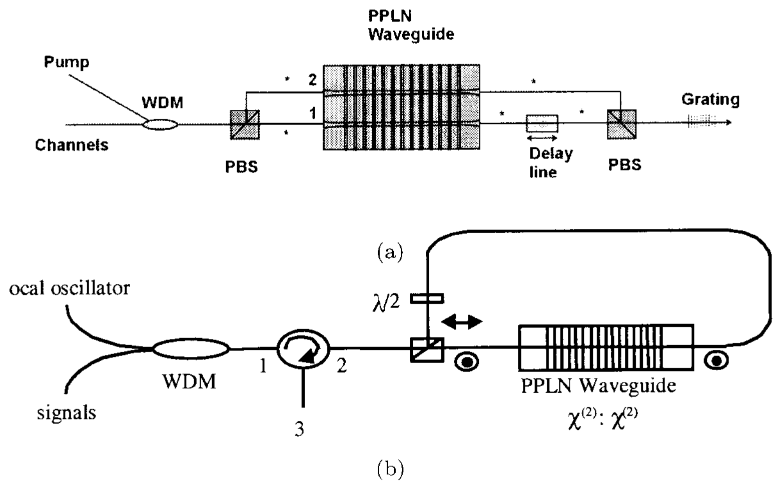

Fig. 9 Two configurations for polarization diversity.

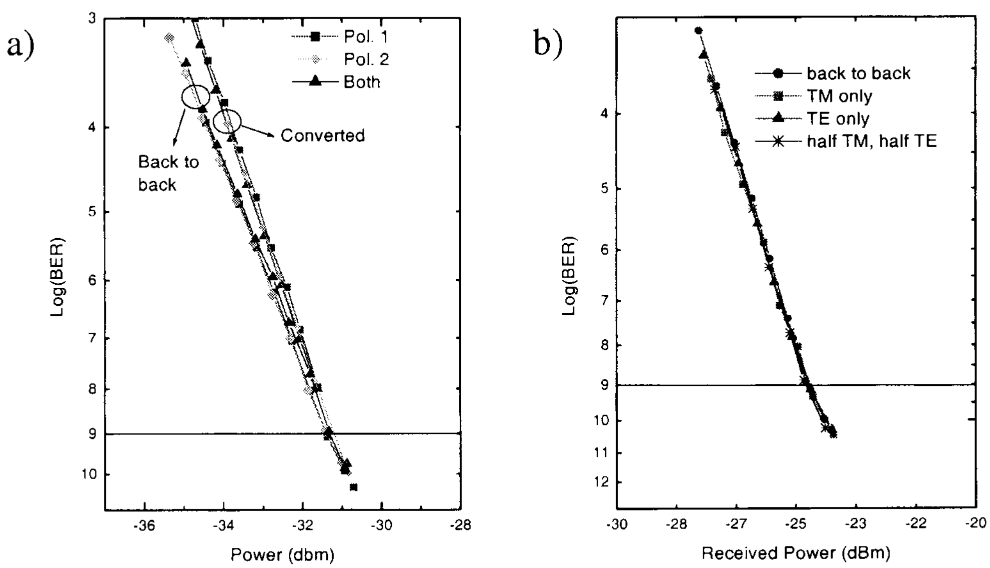

Fig. 10 BER results from polarization diversity experiments (a) using scheme in Fig. 9(a), trace with converted channels in both polarizations is identical to that using only polarization 1; (b) using scheme in Fig. 9(b), all curves are identical to that of the back to back measurement, indicating that the conversion process produces negligible power penalty, and that both polarizations are converted with the same efficiency.

Both of these issues are resolved in the scheme shown in Fig. 9(b). In this case, both polarizations are converted using the same waveguide and follow identical paths. The sample endfaces are angle polished and pigtailed to angle polished fibers in order to prevent reflections that would cause instability and crosstalk between the counter propagating beams. BER curves shown in Fig. 10 indicate that both schemes are effective in essentially eliminating polarization sensitivity.

6. All-Optical Gating

Difference frequency mixing is not the only three-wave mixing interaction of interest. Sum frequency mixing (SFM) can be used to implement a low power all-optical gate [8]. In DFM, the low power signal is amplified during the mixing process, whereas in SFM, the signal wave is depleted during generation of the sum frequency wave. In the simple case of a phasematched interaction, without loss, where the control wave is much stronger than the signal wave (and can be considered undepleted), the evolution of power in the SFM and signal waves is described by Eqs. (1),(2):

$$P_{SFM}(L) = P_{SIG}(0)\frac{\lambda_{SIG}}{\lambda_{SFM}}\sin^2\left(\sqrt{\eta_{nor}P_{CTRL}}L\right) \quad (1)$$

$$P_{SIG}(L) = P_{SIG}(0)\cos^2\left(\sqrt{\eta_{nor}P_{CTRL}}L\right) \quad (2)$$

where L is the interaction length, P_{CTRL} is the con-

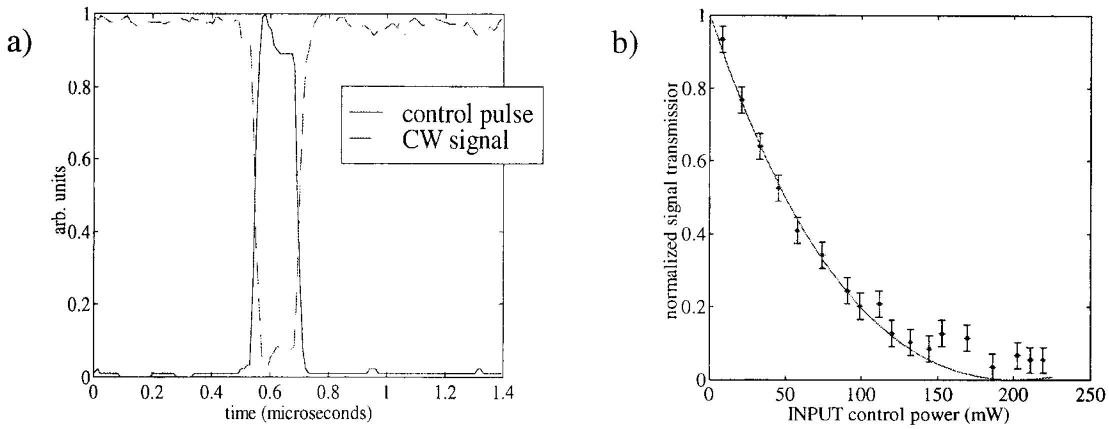

Fig. 11 (a) Typical pulse traces, showing depletion of the signal in the presence of the control pulse. (b) Measured and calculated variation of signal transmission with control power.

trol power, λ_{SFM} and λ_{SIG} are the SFM and signal wavelengths, and η_{nor} is the normalized conversion efficiency. Complete depletion of the signal occurs when the argument of the trigonometric functions equals $\pi/2$. Hence gating of the signal can be accomplished by turning the control power on and off.

Figure 11(a) shows depletion of the CW signal in the presence of the control pulse. One advantage of the nonlinear transfer function of the SFM process is that distortions in the control pulse are suppressed in the depleted signal pulse, making the gating less sensitive to variations in the control pulse level. Figure 11(b) shows a plot of normalized signal transmission as a function of control power. The solid line shows the calculated result obtained by numerical integration of the coupled mode equations describing the SFM process in waveguides, including the propagation losses neglected in obtaining Eqs. (1),(2). The calculation used a normalized internal SFM conversion efficiency of 3390%/W (as determined by measurement of the second harmonic generation efficiency of 847%/W) and typical values of propagation losses at the three wavelengths (0.35 dB/cm at λ_{SIG} and λ_{CTRL}, and 0.70 dB/cm at λ_{SFM}). Nearly complete (96%) extinction of the signal is seen at an input control power of 185 mW, a value in reasonable agreement with theory. The mechanism responsible for the residual 4% is unclear; slight phase mismatch arising from waveguide nonuniformity is one possibility.

Higher contrast can be achieved by placing this device in an interferometer or in a nonlinear optical loop mirror (NOLM [9], Fig. 12). In the absence of the control pulse, the loop is balanced and all of the signal power exits at port 1. When the control is on, signal power travelling in one direction in the loop gets depleted, so that incomplete interference at the 3 dB coupler results in signal power leaving port 2 (at a level 6 dB below the input value). Hence an AND logic function is implemented (there is output only when the signal and control are both on). Power switched to the SFM wave can be used for further signal processing. A similar device has been used to perform efficient optical sampling [10].

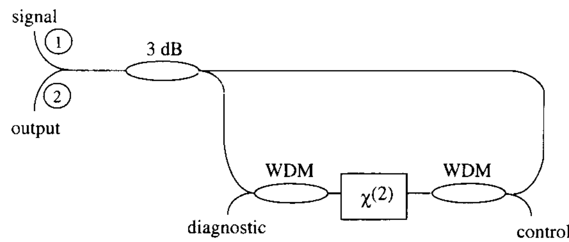

Fig. 12 AND gate using $\chi^{(2)}$ in NOLM configuration.

This experiment does not explore the minimum pulsewidth that can be switched by the device. For the 6 cm-long device presented here, this value is roughly 25 ps. The bandwidth of the device is limited by group velocity walkoff between the three interacting waves, such that the minimum pulsewidth scales inversely with the device length. Hence efficiency and bandwidth can be traded against each other.

7. Summary and Future Work

In summary, we have demonstrated a variety of signal processing functions using three-wave mixing in APE-PPLN waveguides. Future work will seek to improve device performance, using means such as high index cladding layers or buried waveguides, where increased mode overlap can produce large gains in efficiency. One way to eliminate the bandwidth-efficiency tradeoff is known as "quasi-group velocity matching," where after each walk-off length, the faster pulse passes through a delay line integrated into the waveguide structure in order to be resynchronized with the slower pulse. This scheme would allow for high efficiency switching of "arbitrarily" short pulses.

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