Wavelength- and Time-Selective All-Optical Channel Dropping in Periodically Poled Ti : LiNbO$_3$ Channel Waveguides

Y. L. Lee, H. Suche, Y. H. Min, J. H. Lee, W. Grundkötter, V. Quiring, and W. Sohler

***Abstract*—Wavelength- and time-selective channel dropping by sum frequency generation of a 10-GHz channel out of a 4 × 10 GHz optical time-division-multiplexed signal has been demonstrated using two fully packaged Ti : PPLN wavelength converters. Less than −15 dB of channel dropping extinction ratio is observed with average (peak) coupled pump power of 100 mW (2 W).**

***Index Terms*—Nonlinear optics, optical switching, optical waveguide, periodically poled lithium niobate (PPLN), quasi-phase matching, sum frequency generation (SFG).**

I. Introduction

PERIODICALLY poled LiNbO$_3$ (PPLN) waveguides can be used for all-optical wavelength conversion as well as for high-speed all-optical signal processing due to their ultrafast nonlinear optical response, low switching power, and wide conversion bandwidth. In particular, all-optical channel dropping is one of the key functionalities in future reconfigurable photonic networks. First optical parametric switches based on sum frequency generation (SFG) have been demonstrated in bulk LiNbO$_3$, in proton exchanged (APE) and Ti-indiffused PPLN waveguides [1]–[4]. Up to now, wavelength-selective, but not time-selective, channel dropping has been demonstrated.

In this letter, we demonstrate for the first time, ultrafast time- and wavelength-selective channel dropping based on SFG using two fully packaged Ti : PPLN waveguides. The first device was used to generate the wavelength shifted 10-GHz pump for the SFG process in the second PPLN device.

II. Device Fabrication and Packaging

On a 0.5-mm thick 4-in-diameter z-cut LiNbO$_3$ wafer, optical waveguides were fabricated by indiffusion (8.5 h at 1060 °C) of photolithographically defined Ti-stripes (7 μm wide, 98-nm thickness) aligned parallel to the x axis of the crystal. Afterwards, the microdomain structure of 16.6-μm periodicity was generated by the electric field assisted poling technique using liquid electrodes. Details of the poling process are reported elsewhere [5]. Finally, the endfaces of the waveguides were polished to allow endfire coupling of pump and signal waves by butt coupling with fibers. In addition, the endfaces were antireflection-coated to avoid Fabry–Pérot interference effects. The fiber pigtails were mounted on micro-manipulators with a few micrometers separation to the waveguide endfaces. This epoxy-free coupling does not limit the power levels of pump and signal. Moreover, in this way, operation at elevated temperatures up to 200 °C is possible to minimize photorefractive effects and to adjust phase matching [6]. Detailed information on the two packaged devices used in the experiment is given in Table I.

TABLE I
Specifications of the Two Packaged Devices

Name of device	PPLN(1)	PPLN(2)
Length (Effective interaction length)	86 mm 59 mm	77 mm 65 mm
Waveguide loss (TM)	0.11 dB/cm	0.12 dB/cm
SHG efficiency (3 dB bandwidth)	700 %/W 0.20 nm	760 %/W 0.16 nm
Mode size (FWHM) TM-mode, 1550 nm	4.5μm ×3.0μm	4.7μm ×3.4μm
Fibre to fibre insertion loss	5.5 dB (TM)	5.0 dB (TM)

III. Experimental Setup

The experimental setup to demonstrate all-optical ultrafast selective optical time-division-multiplexed (OTDM) channel dropping is shown in Fig. 1. A mode-locked fiber laser, generating 5-ps-long nearly transform limited pulses at $\lambda_s = 1557.08$ nm with 10-GHz repetition rate, was used twofold; therefore, a fiber-optic 3-dB power splitter was inserted. The pulses in the upper branch were combined in a second fiber-optic 3-dB power splitter with the continuous wave (CW)-output ($\lambda_f = 1553.87$ nm) of a tunable extended cavity laser (ECL). Both waves were boosted in a high-power erbium-doped fiber amplifier (HP-EDFA) and simultaneously coupled to the first wavelength converter PPLN (1) operated at 173 °C. The ECL-output served as the fundamental to generate via cascaded difference frequency generation (cDFG)

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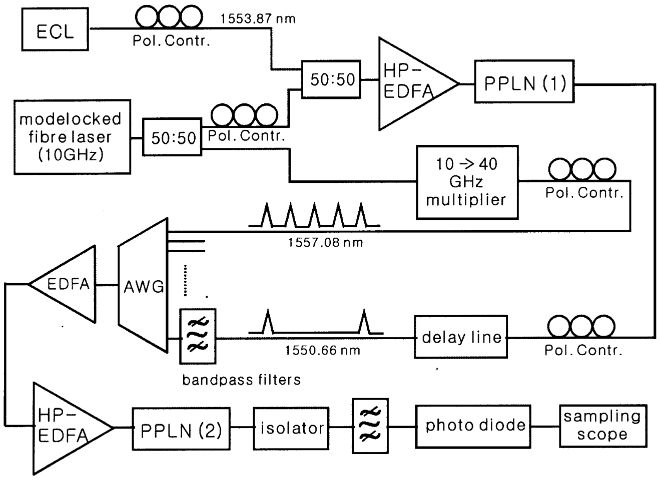

Fig. 1. Experimental setup to demonstrate time- and wavelength-selective channel dropping by SFG.

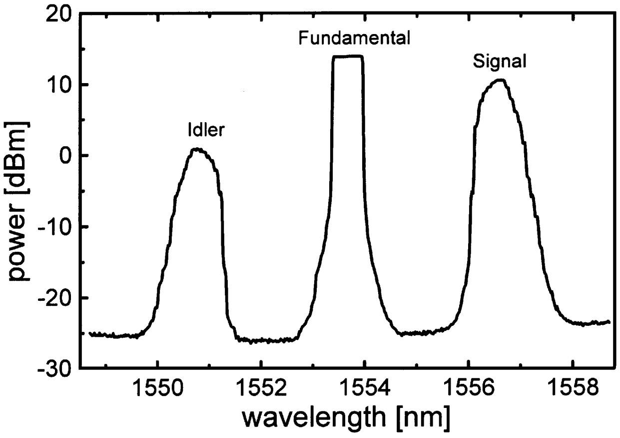

Fig. 2. CDFG in PPLN (1): output power versus wavelength at 0.5-nm resolution bandwidth of the optical spectrum analyzer.

a 10-GHz idler, wavelength-shifted to 1550.66 nm (see Fig. 2). The corresponding conversion efficiency was about -9.5 dB with respect to the transmitted signal power. A tunable delay line has been used to adjust the temporal overlap of the 10-GHz idler pulses, serving as pump for the channel dropping experiment in PPLN (2), with every fourth signal pulse. Subsequently, the output of PPLN (1) passed a bandpass filter to suppress the fundamental and the 10-GHz signal waves as well as most of the amplified spontaneous emission (ASE) of the HP-EDFA.

The pulses of the fiber laser in the lower branch of the power splitter passed a fiber-optic 10 $\rightarrow$ 40-GHz multiplier to simulate a 40-Gb/s OTDM signal. It was superimposed in an arrayed waveguide grating (AWG) with the 10-GHz idler, generated in PPLN (1). Both waves were preamplified in an EDFA, boosted in a second HP-EDFA, and coupled into the second wavelength converter PPLN (2), operated at 171 °C. In PPLN (2), individual OTDM channels of the signal were dropped by time-selective SFG with the boosted idler of PPLN (1). The transmitted sum frequency (SF) output of PPLN (2) was blocked by absorption in an isolator; the transmitted OTDM signal was bandpass filtered to remove the pulsed pump and most of the ASE of the second HP-EDFA. Finally, the filtered OTDM signal was detected using an ultrafast photodiode of 50-GHz bandwidth and monitored using a sampling scope.

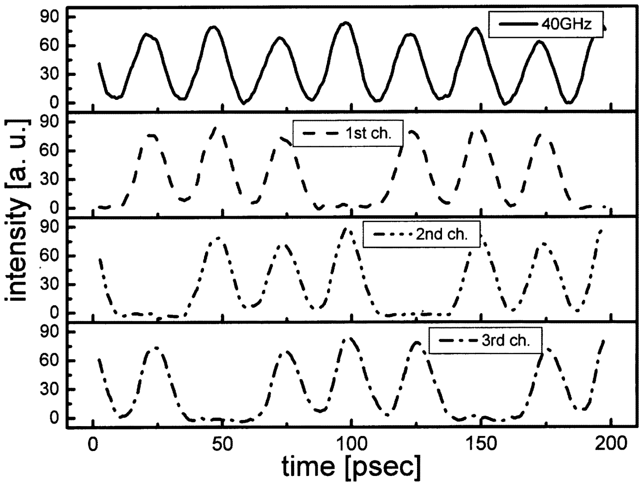

Fig. 3. Selective channel dropping by SFG of individual 10-GHz OTDM channels (lower traces) out of the 40-GHz OTDM signal (upper trace); $\lambda = 1557.08$ nm.

IV. Time-Selective Channel Dropping

If the time delay between the 4 × 10 GHz OTDM signal ($\lambda_s = 1557.08$ nm) and the amplified 10-GHz idler of PPLN (1) serving as pump for PPLN (2) was properly adjusted, SFG was observed leading to a depletion of every fourth signal pulse.

At a coupled average (peak) pump power of 100 mW (2 W), complete depletion of every fourth signal pulse was observed with a channel dropping extinction ratio of < -15 dB. By changing the optical delay of the pump, dropping of individual OTDM channels can be achieved. In Fig. 3, the sampling scope traces for the original 4 × 10 GHz (OTDM) signal and for the dropping of three of the four OTDM channels are shown; the fourth channel was not accessible due to the limited tuning range of the delay line. Fig. 4 shows the signal depletion by SFG as a function of the coupled pump power for both interactions of the signal with CW pump [Fig. 4(a)] and with pulsed [Fig. 4(b)]. In the case of CW interaction, 175 mW of coupled pump power is needed for signal depletion to less than -23 dB. If the interaction of pulses of 5-ps width [full-width at half-maximum (FWHM)] and 10-GHz repetition rate is considered a coupled peak pump power level of 2 W is required for signal depletion to less than -15 dB.

The group velocity mismatch between the sum frequency pulses and the signal and the pump [idler of PPLN(1)] pulses strongly reduces the conversion efficiency in comparison with an interaction of CW waves. As a consequence, broader pump pulses would increase the conversion efficiency and reduce the required pump power. This, however, may limit the temporal resolution for the channel dropping. Using coupled mode theory and the split step fast Fourier transform beam propagation method, our numerical simulation shows an extinction ratio of -15.1 dB. With a broader pump pulse of 7.5-ps width, an improved extinction ratio up to -27 dB is predicted.

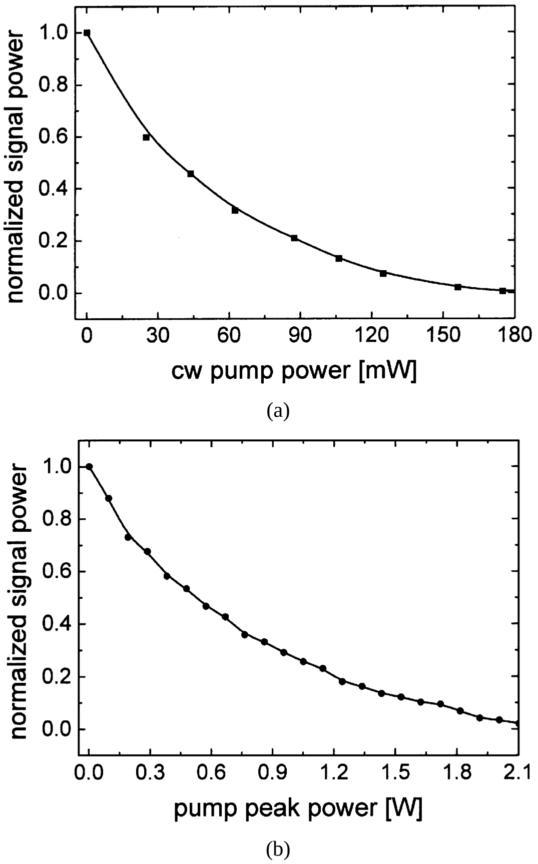

Fig. 4. Signal depletion by SFG versus coupled pump power. (a) For CW waves and (b) for pulse trains of 10-GHz repetition rate and 5-ps pulsewidth (FWHM).

V. CONCLUSION

For the first time, to our knowledge, all-optical wavelength- and time-selective channel dropping based on SFG has been demonstrated using two fully packaged Ti:PPLN waveguide devices. Individual 10-GHz channels of a 4 × 10 GHz OTDM signal have been selectively dropped with an extinction ratio of -15 dB using 100 mW (2 W) of average (peak) pump power. The difference between required pump power levels for optimum signal depletion of CW and pulsed interaction is due to group velocity mismatch effects between the three interacting waves. Therefore, the interaction length for dropping of signal pulses of given width has to be optimized. On the other hand, the dropping extinction ratio for a given device length can be optimized by a proper choice of the pump pulsewidth. For the actual device discussed here, numerical simulations predict an optimum extinction ratio of -27 dB for pump pulses of 7.5-ps width. The dropped channels can be made accessible by subsequent wavelength translation to a free ITU channel using the sum frequency signal together with a second pump in a DFG process [7].

Moreover, polarization-independent channel dropping should be possible using a polarization diversity scheme with automatic differential group delay equalization between both transverse-electric and transverse-magnetic polarization, as demonstrated in [8] for cascaded DFG.

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