Multichannel Wavelength Conversion Exploiting Cascaded Second-Order Nonlinearity in $LiNbO_3$ Waveguides

Junqiang Sun, Wei Liu, Jing Tian, *Member, IEEE*, J. R. Kurz, and M. M. Fejer

***Abstract*—Ten-channel wavelength conversion is achieved by exploiting cascaded second-order nonlinearity in periodically poled $LiNbO_3$ waveguides. No external pump input is required in the converter and conversion efficiency is improved due to the enhancement of pump and signal interaction. Approximate 70-nm conversion bandwidth is realized under pump power less than 25 mW at 1550-nm band.**

***Index Terms*—Nonlinear optics, optical fiber communication, wavelength conversion, wavelength-division multiplexing.**

I. Introduction

All-optical wavelength conversion is expected to be a crucial technique in broad-band dense wavelength-division-multiplexed (DWDM) networks owing to its capability of wavelength reuse, thereby avoiding wavelength channel contentions and facilitating network management [1]. For practical DWDM system applications, requirements for high conversion efficiency, wide wavelength conversion bandwidth, low frequency chirp, and capability to accommodate signals of any format and protocol including analog and frequency modulation must be satisfied. Compared with the previous demonstrated approaches such as cross-gain modulation [2], cross-phase modulation [3], and four-wave mixing [4] in semiconductor optical amplifiers (SOAs), wavelength conversion employing difference frequency generation (DFG) can meet the above requirements and has manifested several advantages: In addition to strict transparency for random modulation rates and formats and without intrinsic frequency chirp, it can simultaneously up and down convert multiple channels with equal efficiencies [5]. DFG-based wavelength conversion has been demonstrated utilizing periodically domain-inverted $LiNbO_3$ (PPLN) [5], and AlGaAs [6] waveguides, showing impressive potentials for DWDM networks. However, $\sim$100-mW pump power at wavelength of 750$\sim$800 nm is required to realize 0-dB conversion efficiency, and it is difficult to simultaneously couple the 780-nm pump and 1.5-μm band signals into the fundamental mode of the waveguide. Wavelength conversion in PPLN waveguides is achieved more conveniently by employing cascaded second-harmonic generation (SHG) and DFG so that all incident signals are in the 1.5-μm band and propagate through the waveguides in single mode. High pump powers ($>$100 mW) at 1.5 μm are required for standard devices, however, high efficiency buried waveguides can reduce the required pump power to 75 mW [7]. In this letter, a novel experimental scheme is presented to enhance conversion efficiency, in which no external pump injection is required and pump light is internally generated inside the proposed configuration. Due to the characteristics of the intracavity pump laser and enhanced pump and signal interaction, conversion efficiency is improved significantly.

Manuscript received February 10, 2003; revised June 10, 2003. This work was supported by the Chinese Natural Science Foundation under Grant 60177015, the DARPA through the Optoelectronics Materials Center, the AFOSR though Contract 49620-02-1-0240, and by the Stanford Optical Signal Processing Collaboration.

J. Sun and W. Liu are with the Department of Optoelectronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: jqsun@hust.edu.cn).

J. Tian is with Spectralane, Inc., Santa Clara, CA 95051 USA.

J. R. Kurz and M. M. Fejer are with the Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305 USA.

Digital Object Identifier 10.1109/LPT.2003.819713

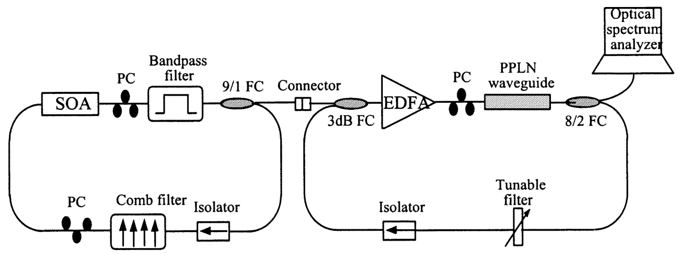

Fig. 1. Experimental arrangement for DFG-based multichannel wavelength conversion. PC: Polarization controller. FC: Fiber coupler.

II. Experimental Setup

The experimental arrangement for DFG-based wavelength conversion is schematically shown in Fig. 1, which includes a multiwavelength laser source and the combination of a tunable ring fiber laser and a DFG-based wavelength converter. The multiwavelength ring laser consists of an SOA, a comb filter, a bandpass filter, an isolator, and polarization controllers. The multiquantum-well SOA serves as a gain medium, which provides the small-signal gain of 20 dB with the gain bandwidth of 50 nm. Two inline polarization controllers are positioned in the ring cavity to compensate the polarization sensitivity caused by the SOA. The comb filter with the wavelength spacing of 1.6 nm determines the resonant modes. The bandpass filter with 18-nm bandwidth is used to inhibit the lasing wavelength region and filter the amplified spontaneous emission (ASE) noise. This bandpass filter can be replaced to obtain different lasing wavelength regions. The output multiwavelength signal is extracted

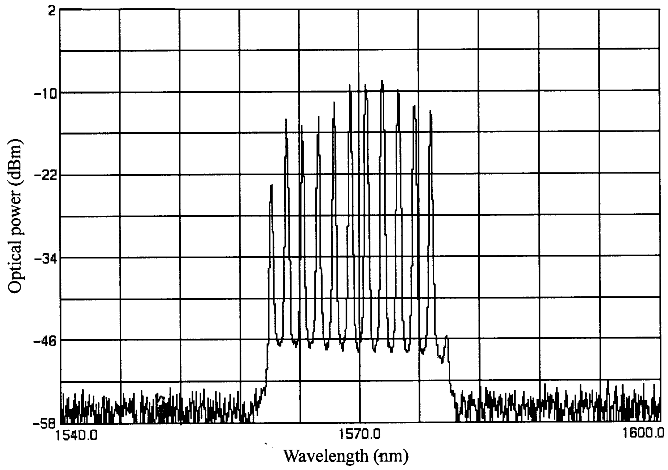

Fig. 2. Output optical spectra from the multiwavelength laser for the bandpass filter with wavelength region of 1561–1579 nm.

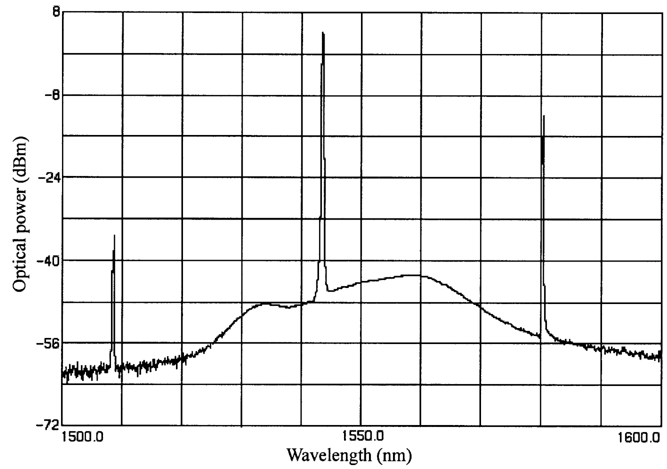

Fig. 3. Measured output spectrum from the wavelength converter for single channel wavelength conversion.

through a 9 : 1 fiber coupler. The tunable ring laser is composed of a tunable Fabry–Pérot filter and a erbium-doped fiber amplifier (EDFA) which can offer the small-signal gain of 25 dB and saturation output power of 27 dBm. Its lasing wavelength can be tuned as a pump wavelength to satisfy the SHG in the periodically poled $LiNbO_3$ (PPLN) waveguide. The waveguide is fabricated by annealed proton exchange in PPLN. The component used in this experiment is 50 mm in length, has quasi-phase-matching (QPM) period of 14.7-μm, waveguide width of 12 μm, and an initial proton exchange depth of 0.8 μm. The device parameters allow phasematching at room temperature between the fundamental mode of the pump at 1544 nm and the fundamental mode of the second-harmonic wave at 772 nm. The fiber-to-fiber coupling loss is estimated about 4.7 dB caused by the reflection losses at the uncoated endfaces, mode mismatching between the fibers and the PPLN waveguide, and intrinsic waveguide losses. Making use of cascaded second-order nonlinearity, DFG-based wavelength conversion can be achieved by means of pump and multichannel signal interaction in PPLN waveguide. The output spectra are monitored by an optical spectrum analyzer with the highest spectral resolution of 0.06 nm.

III. Experimental Results and Discussions

Fig. 2 shows the output spectrum from the multiwavelength laser when the central wavelengths of bandpass filter is chosen at 1570 nm. Ten lasing wavelengths are observed with a fixed channel spacing of 1.6 nm. More than −16-dBm output power for each wavelength is obtained with more than 30-dB signal-to-ASE ratio. The device performance is verified by launching a single channel signal with wavelength of 1580.2 nm into the suggested configuration. Fig. 3 illustrates the measured output spectrum and distinctly displays the wavelength conversion between 1580.2 and 1508.5 nm. The optimum pump wavelength is measured at 1543.5 nm to satisfy the QPM condition when the PPLN waveguide operates at room temperature. In the experiments, the largest conversion efficiency is realized by tuning the Fabry–Pérot filter. From the measured results, it can be estimated that the intracavity pump power is less than 50 mW. It can be concluded that the pump power is

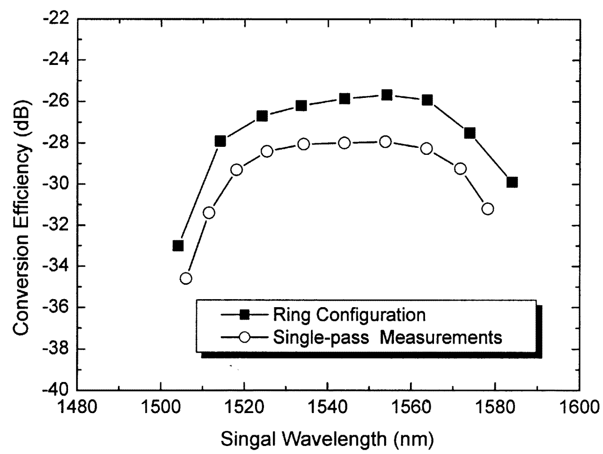

Fig. 4. Conversion efficiency as a function of the input signal wavelength for single-pass and ring configurations. The pump power inside the waveguide (at 1543.5 nm) is about 25 mW.

lowered and the conversion efficiency is improved thanks to the enhancement of pump and signal interaction. Fig. 4 shows the variations of the measured conversion efficiency with the input signal wavelength while keeping the pump wavelength fixed at 1543.5 nm. The conversion efficiency varied by less than 3 dB across the wavelength span of 70 nm, and the fluctuation is less than 1 dB from 1510 to 1570 nm. By keeping the same power and polarization state of the pump light injected into the waveguide as in the ring configuration, the conversion efficiency for the single-pass arrangement is measured and also plotted in Fig. 4. Approximate 3.5-dB enhancement of the conversion efficiency is achieved with our suggested scheme under the input pump power of 25 mW. The improvement of conversion efficiency can be explained due to the following facts. First, in the ring configuration the intracavity laser serves as pump light while the externally amplified signal is used as pump light in the single-pass configuration. Evidently, the linewidth of the intracavity laser is narrower than that of the amplified signal. According to the cascaded second-order nonlinear effect in the PPLN waveguide, the narrower pump light will produce the higher conversion efficiency. Second,

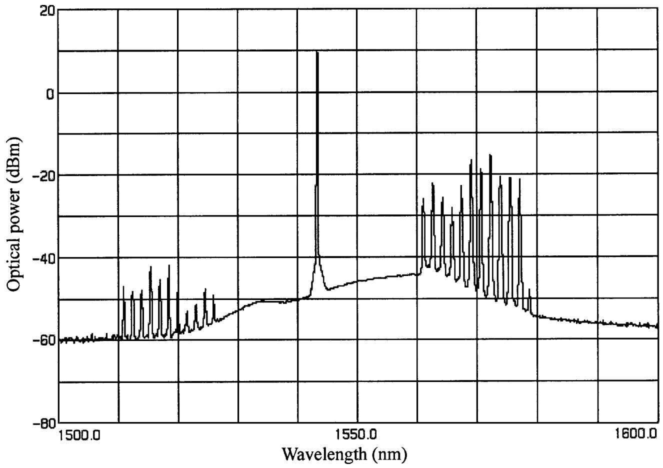

Fig. 5. Measured output spectrum from the wavelength converter for multichannel wavelength conversion with input signal wavelength region of 1561–1579 nm.

transverse mode distributions in the waveguide are different between the amplified signal and the intracavity laser. Lasing is established on the basis of the sustained oscillation and the lasing power is concentrated along the central axis in the PPLN waveguide. Thus, the pump power density in the ring configuration is higher than that in the single-pass configuration. Meanwhile, the lasing wavelength can be easily tuned to align to the pump wavelength required for DFG effect. Therefore, the pump and signal interaction is enhanced and the improvement of conversion efficiency is achieved. Finally, in the ring configuration, the polarization state of the intracavity laser is aligned to the desired polarization states during the process of the adjustment of the polarization controller owing to the fact that lasing is taken place for the minimum polarization-dependent loss. Therefore, almost total intracavity laser involves in the wavelength conversion. Whereas in the single-pass configuration the utilization ratio of the amplified pump light will be decreased due to the polarization state difference for different waveguide structures when the situation of the polarization controller is kept same as in the ring configuration. As a result, the conversion efficiency is consequently impaired. Fig. 5 shows simultaneous multichannel wavelength conversion by the injection of multiwavelength lasing lines into the configuration at 1570-nm band. The results indicate that the conversion efficiencies are almost the same for all the converted channels. The converted signals are the mirror image of the input signals about the pump wavelength. The intracavity pump power is less than 100 mW and about 70-nm wavelength span is realized with our scheme. During the experiment, we find that the strong EDFA ASE noise can be effectively suppressed for the converted signals. This behavior is ascribed to the inverted population depletion owing to the laser oscillation at the pump wavelength. In addition, the PPLN waveguide filters one polarization, removing half of the spontaneous emission in one pass, while keeping the correctly polarized signal. For DFG-based wavelength converters, the pump wavelength can be changed by the design of different QPM period and the adjustment of operation temperature. Moreover, the QPM condition can be further relaxed by introducing various phase-shifting domains into the QPM gratings [8]. Consequently, The lasing wavelengths within the entire EDFA gain bandwidth can be used as the pump wavelength [9]. This implies that broad bandwidth tunable laser from 1400 to 1700 nm can be potentially generated employing our scheme.

IV. Conclusion

A novel multichannel wavelength conversion scheme has been proposed and demonstrated within the 1.5-μm band by exploiting cascaded second-order nonlinearity in $LiNbO_3$ waveguides. Ten lasing wavelengths are generated and converted simultaneously. Approximate 70-nm conversion bandwidth is achieved. Owing to the enhancement of pump and signal interaction, the conversion efficiency is increased and, hence, the pump power is lowered. Our scheme also provides the possibility to realize a broad bandwidth tunable laser source for optical communication applications.

References

[1] S. J. B. Yoo, "Wavelength conversion technologies for WDM network applications," *J. Lightwave Technol.*, vol. 14, pp. 955–966, June 1996.
[2] A. D. Ellis, A. E. Kelly, D. Nesset, D. Pitcher, D. G. Moodie, and R. Kashyap, "Error free 100 Gbit/s wavelength conversion using grating assisted cross-gain modulation in 2 mm long semiconductor amplifier," *Electron. Lett.*, vol. 43, no. 20, pp. 1958–1959, 1998.
[3] C. Joergensen, S. L. Danielsen, T. Durhuus, B. Mikkelsen, K. E. Stubkaer, N. Vodjdani, F. Ratovelomanana, A. Enard, G. Glastre, D. Rondi, and R. Blondeau, "Wavelength conversion by optimized monolithic integrated Mach–Zehnder interferometer," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 521–523, Apr. 1996.
[4] M. C. Tatham, "20 nm optical wavelength conversion using nondegenerate four-wave-mixing," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 1303–1306, Nov. 1993.
[5] M. H. Chou, I. Brener, M. M. Fejer, E. E. Chaban, and S. B. Christman, "1.5-μm-band wavelength conversion based on cascaded second-order nonlinearity in $LiNbO_3$ waveguides," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 653–655, June 1999.
[6] S. J. B. Yoo, C. Caneau, R. Bhat, M. A. Koza, A. Rajhel, and N. Antoniades, "Wavelength conversion by difference frequency generation in AlGaAs waveguides with periodic domain inversion achieved by wafer bonding," *Appl. Phys. Lett.*, vol. 68, no. 19, pp. 2609–2611, 1996.
[7] K. R. Parameswaran, R. K. Route, J. R. Kurz, R. V. Roussev, M. M. Fejer, and M. Fujimura, "Highly efficient second-harmonic generation in buried waveguides formed by annealed and reverse proton exchange in periodically poled lithium niobate," *Opt. Lett.*, vol. 27, no. 3, pp. 179–181, 2002.
[8] L. Wei, J. Sun, and J. Kurz, "Bandwidth and tunability enhancement of wavelength conversion by quasiphase-matching difference frequency generation," *Opt. Commun.*, vol. 216, no. 1–3, pp. 239–246, 2003.
[9] K. Gallo, G. Assanto, and G. Stegeman, "Efficient wavelength shifting over the erbium amplifier bandwidth via cascaded second order processes in lithium niobate waveguides," *Appl. Phys. Lett.*, vol. 71, no. 8, pp. 1020–1022, 1997.