European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

L-band Mode and Wavelength Conversion in a Periodically Poled Lithium Niobate Ridge Waveguide

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Abstract *We present simultaneous mode and wavelength conversion over wavelengths from 1570 nm to 1610 nm based on intermodal difference frequency generation in a periodically poled lithium niobate ridge waveguide. A conversion efficiency of -10.7 dB is observed owing to the high quadratic nonlinearity.*

Introduction

Space division multiplexing (SDM), where data is transmitted on multiple spatially distinct channels within each fibre strand, has been proposed as a cost-effective approach to the scaling of data transmission capacity in future optical communication networks [1]. Optical components that enable spatial mode conversion and/or wavelength conversion are likely to be indispensable in the longer term implementation of a functional fully SDM network and provide shorter term opportunities to upgrade existing infrastructure based on standard single mode fibres (SSMF) through hybrid SDM-SSMF systems. This provides the motivation to explore the interactions between spatial modes in optical fibres and nonlinear waveguides.

Use of intermodal four wave mixing (FWM) for mode and wavelength conversion has already been demonstrated using material platforms like silica fibres and silicon waveguides [2-6], with conversion efficiencies of more than -10 dB [2], and operating bandwidths exceeding 40 nm demonstrated [4]. However, such $\chi^{(3)}$-nonlinearity based material platforms usually require phase-modulated pumps to suppress stimulated Brillouin scattering and high pump power (>1 W of peak power) to increase the nonlinear efficiency. Furthermore, the requirement to precisely engineer the mode-dependent dispersion adds complexity to the design and fabrication of devices. Periodically poled lithium niobate (PPLN) waveguides are a promising alternative candidate for nonlinear frequency conversion by virtue of their unique characteristics. These include a large second order susceptibility which enables a very high conversion efficiency from a short device length, compatibility with multi-channel conversion and transparency to data modulation format, and operation over a wide spectral range that can extend from 0.35 μm to 4.5 μm [7]. Moreover, it is possible to control and customise the operating wavelength range and the detailed quasi-phase-match (QPM) properties over wide ranges by engineering the poling period, the dimension of the waveguide cross-section and the refractive index profile [7]. PPLN waveguides have been developed and studied for applications such as wavelength conversion in telecommunications, molecular spectroscopy and quantum science and technology [7-9]. However, the potential use of intermodal parametric processes in PPLN waveguides has received relatively little attention.

Intermodal sum frequency generation has been demonstrated in few-mode graded-index PPLN waveguides for spatial mode demultiplexing in both classical and quantum communication [10, 11]. Intermodal optical parametric generation was reported in a proton-exchange PPLN waveguide with an asymmetric Y junction design for spatially demultiplexing signal-idler pairs near degeneracy [12]. However, high-peak-power pulsed pump lasers were required to enhance the parametric process in the works mentioned above, which is not

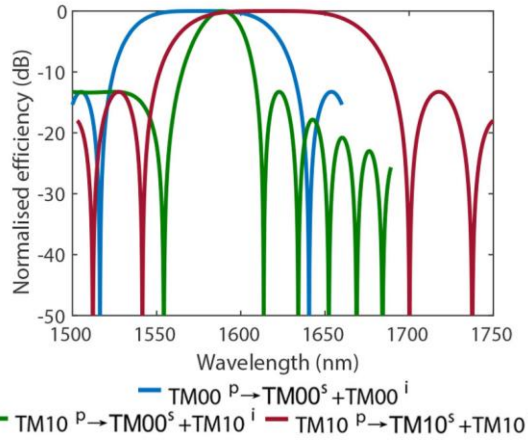

Fig. 1: Calculated normalised efficiency of three parametric processes as a function of wavelength in a multimode PPLN waveguide (blue: intramodal TM00-mode DFG; green: intermodal DFG; red: intramodal TM10-mode DFG).

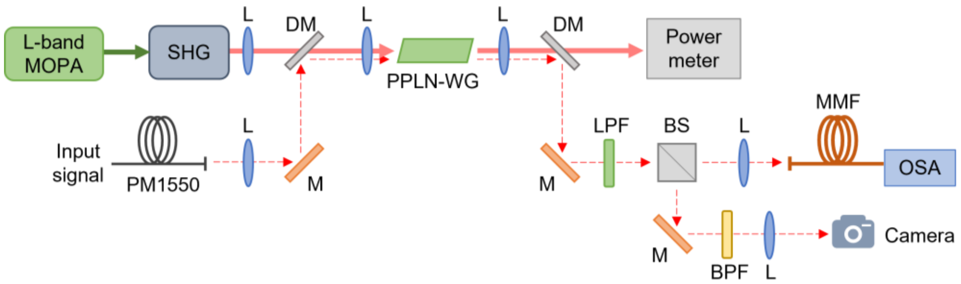

Fig. 2: Schematic of the intermodal DFG experiment. BPF: band pass filter; BS: 50:50 beam splitter; DM: dichroic mirror; L: lens; LPF: long pass filter; M: mirror; MMF: multimode fibre; MOPA: master oscillator power amplifier; OSA: optical spectrum analyser; PPLN-WG: periodically poled lithium niobate waveguide; SHG: second harmonic generation.

compatible with use in high-speed telecommunication systems. In contrast, PPLN ridge waveguides offer multiple advantages such as a large nonlinear coefficient, good mode confinement, high power handling and good long-term stability [7], and these have become the technology of choice for the development of many practical nonlinear frequency conversion systems.

In this work, to the best of our knowledge, we demonstrate for the first time simultaneous mode and wavelength conversion of continuous-wave (CW) L-band signals by intermodal difference frequency generation (DFG) in a multimode PPLN ridge waveguide. Figure 1 shows the QPM conditions for three different DFG processes ($TM00^p \rightarrow TM00^s + TM00^i$; $TM10^p \rightarrow TM00^s + TM10^i$; $TM10^p \rightarrow TM10^s + TM10^i$) in our PPLN waveguide at the same operating temperature of 29.8 °C. The pump wavelengths and the phase-match bandwidth of these three DFG processes are distinctly different. Note that the signal can be in either the TM00 mode or TM10 mode in the intermodal DFG process shown by the green line. A TM00-mode signal implementation is chosen in our demonstration. A pump laser emitting at 794.3 nm in the TM10 mode can be used to achieve the intermodal phase matching according to the calculation shown in Fig. 1.

Experimental setup

The experimental setup used to characterise intermodal DFG in our PPLN waveguide is shown in Fig. 2. The step-index PPLN waveguide (NTT Electronics) has a direct-bonded ridge waveguide structure with a width of 12.5 μm, a height of 10.9 μm, a length of 34 mm and a poling period of 19.15 μm, which supports multimode propagation at both 7xx nm and 15xx nm. The end facets of the waveguide chip are angle-polished with anti-reflection coating at the designed wavelengths.

To meet the phase-match condition of the intermodal DFG process, we built a pump source using an L-band master oscillator power amplifier (MOPA) seeded by a narrow-linewidth laser at 1588.6 nm and a subsequent frequency-doubling stage based on another PPLN waveguide. This in-house built pump source provides up to 700 mW of output power at 794.3 nm in the fundamental mode. Both the pump beam (794.3 nm) and the signal beam (15xx nm) from a tuneable laser were linearly polarised and their polarisation states were aligned with the waveguide to maximise the nonlinear conversion efficiency under type-0 ($e \rightarrow e + e$) phase matching. The pump and the signal were combined using a dichroic mirror and then coupled into the PPLN waveguide using aspheric lenses. A similar dichroic mirror was placed at the waveguide output to separate the signal and the generated idler from the pump. The throughput pump power was monitored by a power meter. A long pass filter (LPF) (>1200 nm) was used to remove any unwanted pump beam to allow ready characterisation of the signal and the idler beams. A 50:50 beam splitter (BS) was placed after the LPF to divide the output, thereby allowing simultaneous measurement of the signal/idler spectrum and modal image. Note that a multimode fibre was used to fully collect the TM00 mode signal and the generated TM10 mode idler for spectral analysis. A band pass filter (BPF) was placed before the camera to enable separation of the signal-idler pair and subsequent imaging of the individual signal and idler beams.

Results and discussion

To examine the intermodal DFG process ($TM10^p \rightarrow TM00^s + TM10^i$), we first launched the LP01 signal from a single-mode fibre into the PPLN waveguide and excited the TM00 mode. The throughput signal image (λ=1600 nm) in Fig. 3(a) shows that the TM00 mode was predominantly excited in our waveguide. Due to the lack of availability of a suitable spatial light modulator at 794.3 nm in our lab, the fundamental-mode output of our pump source cannot be transformed into an ideal LP11-shaped beam as required for optimum launch into the TM10 mode in the PPLN waveguide. Consequently, a simple offset launch technique

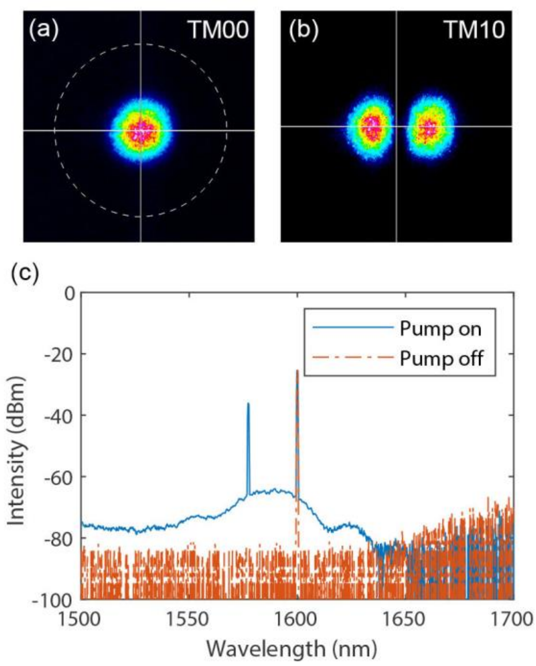

Fig. 3: Images of (a) the throughput signal beam and (b) the idler generated from the intermodal DFG process; (c) output spectrum measured from the multimode fibre.

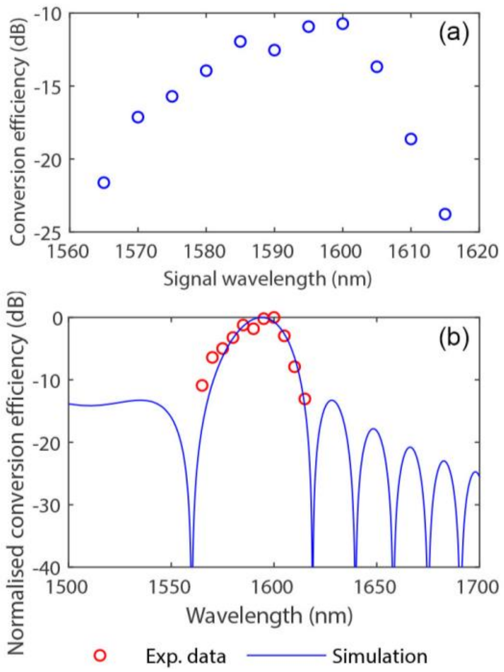

Fig. 4: (a) Conversion efficiency measured at different input signal wavelength; (b) measured and calculated normalised conversion efficiency.

was employed to excite higher order modes in the waveguide. The spectral intensity and the image of the generated idler mode were monitored to enable optimisation of the TM10 mode coupling efficiency. Figure 3(b) illustrates the modal image of the generated idler at the wavelength of 1577.4 nm, which shows a clear TM10 mode profile.

The output spectrum when the launched pump power was kept at 620 mW and the measured throughput pump power was 355 mW is plotted in Fig. 3(c). The input signal power was set to -15 dBm. The total insertion loss of the system from the signal input to the multimode fibre output was measured to be ~10 dB. Note that the 50:50 beam splitter introduces 3.5-dB loss and could easily be removed from the system. Note that the combined propagation loss and signal coupling loss of the waveguide was about 2.2 dB. The conversion efficiency, defined as the ratio of the output idler power to the output signal power, was -10.7 dB at the signal wavelength of 1600 nm. The conversion efficiency is similar to that achieved in previous work [2], in which a total peak power of 2.24 W was used to pump a 1-km-long three-mode fibre. However, note that in this demonstration only a relatively small proportion of the incident pump power was actually launched into the TM10 mode and consequently contributed to the intermodal DFG process (<50 mW of required pump power to achieve -10.7 dB of conversion efficiency according to our intermodal DFG simulation). Therefore, we believe that the nonlinear conversion efficiency could be significantly improved by more efficient pump launching, e.g., by suitable adaptive spatial mode shaping.

Under the same launch condition, the input signal wavelength was tuned from 1565 nm to 1615 nm to measure the operable bandwidth of this intermodal parametric process. In Fig. 4(a), the measured 10-dB conversion bandwidth is seen to be 40 nm (1570-1610 nm). The results are normalised and compared with our numerical simulations. A good match between the experimental results and the simulations can be seen in Fig. 4(b). Additionally, our calculations suggest that the normalised conversion efficiency is spectrally asymmetric with respect to the wavelength at which the phase mismatch is zero. This spectral asymmetry results from the intrinsic interactions between waves in different spatial modes in an intermodal parametric process and is in contrast to intramodal parametric processes which exhibit symmetric phase-mismatch spectra (see Fig. 1).

Conclusion

A simultaneous mode and wavelength converter for CW signals in the L band (1570-1610 nm) has been demonstrated based on intermodal DFG in a PPLN ridge waveguide at a conversion efficiency of -10.7 dB. Such devices have great potential for use in future SDM-SSMF networks.

Acknowledgements

This work is supported by the collaboration project between the Optoelectronics Research Centre and HiSilicon Optoelectronics Co., Ltd..

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