L- to U-Band Wavelength Conversion Based on Intermodal Four-Wave Mixing on-Chip

Valerio Vitali,[1,2,*] Kyle R. H. Bottrill,[1] Thalía Domínguez Bucio,[1] Hao Liu,[1] José Manuel Luque González,[3] Francisco Jurado-Romero,[3] Alejandro Ortega-Moñux,[3] Glenn Churchill,[1] James C. Gates,[1] James A. Hillier,[4] Nikolaos Kalfagiannis,[4] Daniele Melati,[5] Jens H. Schmid,[6] Ilaria Cristiani,[2] Pavel Cheben,[6] J. Gonzalo Wangüemert-Pérez,[3] Íñigo Molina-Fernández,[3] Frederic Gardes,[1] Cosimo Lacava,[2] and Periklis Petropoulos[1]

[1] *Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom*
[2] *Electrical, Computer and Biomedical Engineering Department, University of Pavia, Pavia, 27100, Italy*
[3] *Telecommunication Research Institute (TELMA), Universidad de Málaga, 29010 Málaga, Spain*
[4] *School of Science and Technology, Nottingham Trent University, Nottingham, NG11 8NS, United Kingdom*
[5] *Centre de Nanosciences et de Nanotechnologies, Université Paris-Saclay, CNRS, 91120 Palaiseau, France*
[6] *Advanced Electronics and Photonics Research Center, National Research Council Canada, Ottawa, ON K1A 0R6, Canada*

[*] *valerio.vitali@unipv.it*

Abstract: We report here a broadband Si-rich silicon nitride wavelength converter based on intermodal four-wave mixing with on-chip mode multiplexing and de-multiplexing functionalities. L- to U-band wavelength conversion of 40-Gbps QPSK optical signals is demonstrated.

1. Introduction

The rapid expansion of global internet traffic has generated a significant demand for advanced optical fiber communication systems characterized by high capacity and flexibility. In the last decade, huge efforts have been devoted to exploiting spectral bands outside the conventional C-band (1530 - 1565 nm) [1]. A promising route to increase the capacity of current networks is represented by the use of the adjacent L- (1565 - 1625 nm) and U-bands (1625 - 1675 nm). In these systems, the ability to manipulate optical wavelengths is critical for enhancing the systems' flexibility. Optical devices relying on third-order nonlinearities could be employed to manipulate wavelength components using well-studied nonlinear processes, such as those based on four-wave mixing (FWM). In this regard, most of the reported demonstrations have exploited intramodal FWM processes, i.e. where all the waves are in the same optical spatial mode of the waveguide. In recent years, the use of intermodal FWM (IM-FWM) processes has attracted significant interest in all-optical processing [2]. Indeed, the use of distinct modes of the same waveguide gives more flexibility in the waveguide dispersion engineering and opens new avenues in the design of wavelength converters operating over a broad wavelength range across multiple spectral bands. In this work, we demonstrate a Si-rich silicon nitride (SRSN) wavelength converter based on Bragg scattering (BS)-IM-FWM and we employ the proposed system for L- to U-band wavelength conversion of 40-Gbps QPSK optical signals.

2. Device configuration and experimental results

The system was designed to perform BS-IM-FWM between two pumps (P_1 and P_2) placed in the TE_{00} mode of a multimode SRSN waveguide (refractive index of 2.41 at 1550 nm) and a signal placed in the TE_{10} mode, allowing the generation of two idlers (a red BS idler at longer wavelengths, $I_{BS,r}$, and a blue BS idler at shorter wavelengths, $I_{BS,b}$) in the TE_{10} mode. The layout of the device is shown in Fig. 1 (a). Two pumps were coupled into port 1 of the device while the signal was coupled into port 2 by using a two-fiber array (FA) consisting of two polarization-maintaining (PM) lensed optical fibers. A mode-multiplexer (MUX), consisting of a multimode interference (MMI) coupler, a 90° phase shifter (PS), and a Y-junction, allowed converting the signal into the TE_{10} mode of the multimode waveguide while keeping the two pumps in the TE_{00} mode, following the design in [2]. The idlers were then generated through BS-IM-FWM in the multimode waveguide, converted into the TE_{00} mode by the mode-demultiplexer (DEMUX), and sent to port 4. An output FA was finally employed to collect all the waves from the device. The multimode waveguide was designed to achieve phase matching between P_1 placed at 1540 nm and the signal S at 1610 nm. Fig. 2 (b) shows the measured conversion efficiency (CE) for $I_{BS,r}$ as a function of the signal wavelength λ_S with P_2 placed at 1570 nm. As can be seen, the device allows flexible positioning of the signal wavelength around the nominal value of 1610 nm, with a 3dB bandwidth of $\approx$ 26 nm.

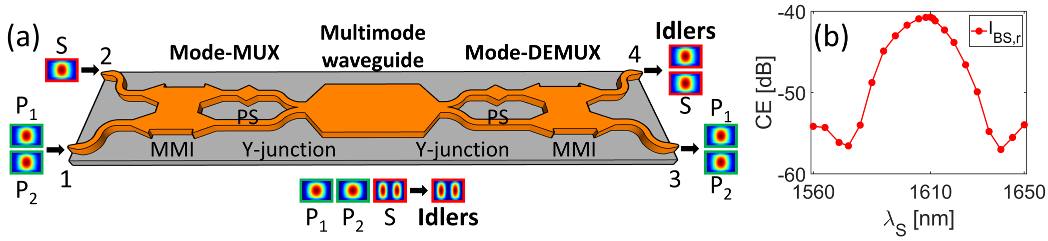

Fig. 1. (a) Layout of the BS-IM-FWM-based wavelength converter; (b) CE as a function of the signal wavelength for $I_{BS,r}$ with P_1 and P_2 wavelengths fixed at 1540 and 1570 nm, respectively.

This device was used to convert modulated L-band signals in the range 1605-1615 nm to the U-band in the range 1638-1648 nm. The setup that was used is shown in Fig. 2 (a). A 40-Gbps single polarization quadrature phase-shift keying (QPSK) signal was generated by modulating a tunable, L-band CW laser with an IQ modulator to carry a 2^{15}-1 pseudo-random bit sequence (PRBS). The signal was then amplified by an L-band Erbium-doped fiber amplifier (EDFA) and coupled into port 2 of the device. The converted U-band idler and the residual signal were then collected at port 4 of the device and sent to the receiver, which consisted of a variable optical attenuator (VOA), a custom-built counter-pumped U-band Raman amplifier (based on the design reported in [3]) to amplify the U-band idler, an optical band-pass filter (OBPF) consisting of a tunable thin-film filter with 0.6 nm 3dB bandwidth and finally an intradyne coherent detector (RX). The VOA was used to control the optical signal-to-noise ratio (OSNR) after the Raman amplifier. Digital, matched, root-raised-cosine filtering was used at both the transmitter and receiver. Fig. 2 (b) shows the bit error rate (BER) curves as a function of the OSNR both of the converted U-band idlers and the back-to-back (B2B) L-band signals (in which case the Raman amplifier was replaced with an L-band EDFA in the receiver side). As can be seen, the U-band idlers were successfully received with a sensitivity penalty in the range ≈ 2 - 4 dB for the three considered signal wavelengths of 1605, 1610, and 1615 nm.

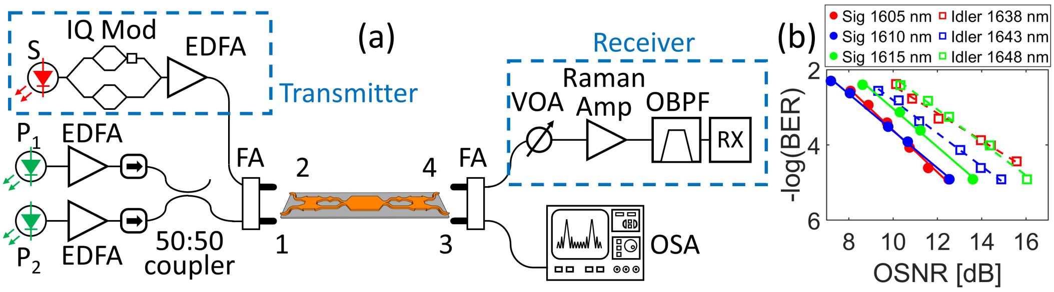

Fig. 2. (a) Experimental setup for the all-optical wavelength conversion experiments of the modulated L-band signals; (b) experimentally measured BER as a function of OSNR.

3. Conclusions

A SRSN wavelength converter based on the use of the BS-IM-FWM process was demonstrated. The system allows broadband wavelength conversion thanks to the dispersion engineering of distinct spatial modes of the same nonlinear multimode waveguide and the advanced design of broadband mode-MUX and mode-DEMUX components on-chip. L- to U-band wavelength conversion of 40-Gbps QPSK optical signals was demonstrated. **Acknowledgements**: This research was funded by the UK's EPSRC through grant EP/T007303/1.

References

1. J. Renaudier, et al., "Devices and Fibers for Ultrawideband Optical Communications," Proceedings of the IEEE (2022).
2. V. Vitali, et al., "Fully Integrated Si-Rich Silicon Nitride Wavelength Converter Based on Bragg Scattering Intermodal Four-Wave Mixing," in 2023 European Conference on Optical Communications (ECOC), Th.A.4.4 (IEEE, 2023).
3. N. Taengnoi, et al., "Ultra-Long-Span U-band Transmission Enabled by Incoherently Pumped Raman Amplification," J. Light. Technol. (2023).