Generation and Coherent Detection of 2-µm-band WDM-QPSK Signals by On-chip Spectral Translation

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Abstract: We have proposed and demonstrated the generation and coherent detection of 2-µm-band I/Q modulated signals for the first time using on-chip spectral translation. 6×32 Gbaud WDM-QPSK signals exhibit BERs below the 7% HD-FEC threshold. © 2020 The Author(s)

1. Introduction

Thriving internet services such as virtual reality and social networking have spurred research into advanced optical communication technologies aiming for sustainable increases in the overall transmission capacity [1]. Attempts to explore alternative frequency bands are gaining new research interest. The 2-µm band is of special interest due to its unique advantages. Firstly, the thulium-doped fibre amplifier (TDFA) can provide more than 200 nm amplification bandwidth in the 2-µm band [2, 3], where the signal can be relayed over long distances with low cost, fibre-based amplifiers. Secondly, the 2-µm band is promising for low-latency transmission in the low loss transmission window of hollow-core fibres [4-6], of interest for latency-sensitive applications such as datacentre interconnects. Thirdly, the 2-µm band represents an attractive spectral window for silicon photonics where two-photon absorption can be reduced [7, 8], enabling advanced on-chip signal processing. Recent 2-µm-band transmission demonstrations have utilised intensity-modulated wavelength-division multiplexing (WDM) [9, 10] or discrete multi-tone modulation [11] to increase the overall transmission capacity. However, these direct-detection based systems with dense-WDM (DWDM) for higher capacity are difficulty to DWDM-demultiplex and are not preferred for spectral efficiency and receiver sensitivity. In order to efficiently utilise the 2-µm band with high spectral efficiency, advanced modulation formats and coherent detection are required. However, the essential devices such as I/Q modulators and coherent receivers are still in their infancy in the 2-µm band compared to off-the-shelf devices in the 1.55-µm band.

Therefore, in this paper, we propose and demonstrate an on-chip spectral translation scheme for the generation and coherent detection of 2-µm band WDM-QPSK signals based on AlGaAsOI nanowaveguides. 6 WDM × 32 Gbaud QPSK channels are generated in the 2-µm band through spectral translation from the 1.55-µm band. The 2-µm band signal is subsequently translated back to the 1.55-µm band for convenient coherent detection. A bit-error ratio (BER) performance below hard-decision forward error correction (HD-FEC) threshold was achieved for all six channels, achieving a net rate of 358.8 Gbit/s, assuming a 7% overhead. To the best of our knowledge, this is the first demonstration of the generation and coherent detection of advanced I/Q modulated signals in the 2-µm band.

2. Principle

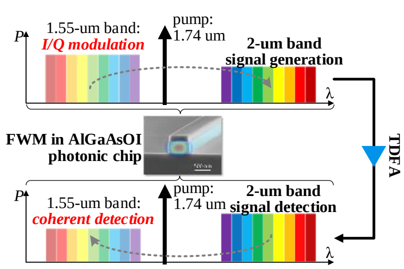

Fig. 1. Principle of the generation and coherent detection of 2-µm band WDM-QPSK signals by spectral translation.

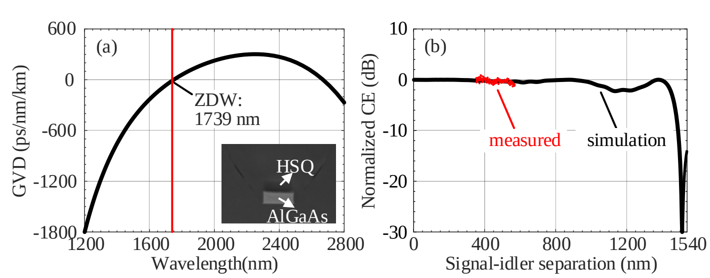

Fig. 2. (a) Dispersion of AlGaAsOI nanowaveguide with dimension 350×920 nm^2 (inset: cross-section SEM image of the AlGaAsOI nanowaveguide sample) and (b) simulated normalized CE (black curve) and measured CE (red dots).

Figure 1 shows the principle of our approach. WDM channels with advanced modulation formats (6 QPSK channels in this experiment) can easily be generated in the 1.55-µm band using high-performance off-the-shelf commercial devices. The 1.55-µm band channels can then be jointly spectrally translated to the 2-µm band with a pump signal around 1.74 µm, using four-wave mixing in a highly nonlinear device. The 2-µm band signal can then be spectrally translated back to the 1.55-µm band where mature coherent detection devices exist.

Two great challenges exist in this experiment. Firstly, it is essential to generate a sufficiently intense continuous-wave pump beam in the 1.74-µm region. Secondly, the highly nonlinear device should provide not only a large translation bandwidth of >450 nm but also a sufficiently high conversion efficiency to provide an acceptable overall optical-to-noise ratio (OSNR) for signal detection. In our experiment, an all-fibre short-wavelength TDFA [12] was developed to provide gain centred around 1739 nm and the maximum achievable output power was higher than 500 mW (with >40 dB OSNR). We selected AlGaAsOI as the nonlinear waveguide platform to fulfil the efficiency and bandwidth requirements of spectral translation. The inherent material nonlinearities and high-index contrast of AlGaAsOI offer an extremely high nonlinearity [13] and efficient dispersion engineering of waveguides [14]. The bandgap of AlGaAs can be engineered by changing the aluminium concentration so that two-photon absorption can be avoided when pumping at 1739 nm to ensure a high conversion efficiency.

The AlGaAsOI wafer was fabricated using a wafer-bonding and substrate removal [15] and the nano-waveguides are patterned by optimized electron-beam lithography with hydrogen silsesquioxane (HSQ) resist followed by dry-etching. The used AlGaAsOI nanowaveguides in this proof-of-concept experiment were designed to be 350 nm in height and 920 nm in width such that the zero-dispersion wavelength (ZDW) is located around 1739 nm, as shown in Fig. 2(a). The inset of Fig. 2(a) shows a scanning electron microscope (SEM) image of the cross-section of the fabricated AlGaAsOI nanowaveguide. Though the waveguide supports high-order waveguide modes, the waveguide is inversely tapered at both sample facets to ensure single-mode operation. The normalized simulated and measured conversion efficiency (CE) [16] of this waveguide are shown in Fig. 2(b). We can see that the AlGaAsOI nanowaveguide exhibits a flat conversion band over 1000 nm with an average measured conversion efficiency of around -23 dB and a variation of less than 2 dB across the 1.55-µm band.

3. Experimental setups

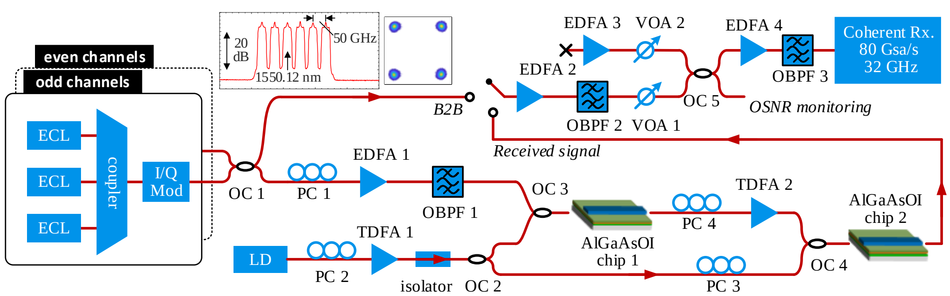

Fig. 3. Experimental setup. (PC: polarization controller; OBPF: optical bandpass filter.)

Figure 3 shows the experimental setup. Six 50-GHz spaced external cavity lasers (ECLs) centred around 193.4 THz with linewidth ~10 kHz are grouped into odd and even channels and then QPSK modulated by two I/Q modulators. The 32 Gbaud I/Q signals are generated from an arbitrary waveform generator with a sampling rate of 64 GSa/s, a roll-off factor of 0.01, and a symbol length of 131072 from a pseudo-random binary sequence of 223-1 length. The QPSK modulated odd and even channels are then combined to form the 6-channel WDM signal. The WDM signal is amplified (EDFA 1) and filtered (OBPF 1), before being merged with a part of the pump, and launched into the first AlGaAsOI nanowire. A distributed feedback (DFB) laser (Eblana EP1742-DM-B, working at 1739.2 nm with 7-dBm output power and < 2-MHz linewidth) was used as a seed laser and amplified to 26.6 dBm through the in-house made TDFA1 to realise the pump source. An optical isolator with 1.1 dB insertion loss at 1.74 µm is included to avoid unwanted optical reflections. A 3-dB coupler (OC 2) is used to split the pump into two tributaries with 22 dBm and 23 dBm optical power for the first and second spectral translation stages, respectively. The isolator and the coupler are not specifically designed for the 1.74-µm band, thus the extra loss and the imbalanced splitting ratio.

A 3-dB coupler (OC 3) is used to combine the pump with the 1.55-µm band WDM signal. The optical power at the input of the AlGaAsOI chip is 18 dBm and 20 dBm for the signal and the pump, respectively. The fibre-to-fibre coupling losses for the AlGaAsOI chip are 10 dB, 11.2 and 12 dB for the 1.55-µm band, 1.74-µm pump, and 2-µm band, respectively. Therefore, the launched power into the AlGaAsOI nanowaveguide for the signal and pump is 13 dBm and 14.4 dBm, respectively. The generated 2-µm band WDM signal is centred around 1980 nm, resulting in a spectral translation of 430 nm. To translate back again to the 1.55-µm band, the 2-µm band WDM signal is amplified by TDFA 2 to 26 dBm and combined with the other tributary of the pump using a 2-µm-band 3-dB optical coupler (OC 4) and injected into the second AlGaAsOI nanowaveguide. The optical power launched to the

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AlGaAsOI chip 2 is 16 dBm and 15.2 dBm, for the signal and the pump, respectively. TDFA 2 also works as a bandpass filter to suppress the 1.74-µm pump and the 1.55-µm signal after the first AlGaAsOI chip.

The output of the spectrally back-translated 1.55-µm signal from the second chip is launched into EDFA 2 and further filtered by OBPF 2. EDFA 2 also suppresses the 1.74-µm pump and the 2-µm signal. The 1.55-µm signal is then launched into a preamplified optical receiver consisting of EDFA 4, OBPF 3, and a coherent receiver working at a sampling rate of 80 GSa/s and an analogue bandwidth of 32 GHz. A noise-loading module consisting of EDFA 3 and VOA 2 is used to evaluate the BER performance for various OSNR values. Four 4-million-sample records for each OSNR of each WDM channel is used for the offline digital signal processing, including a 71-tap adaptive linear equalisation based on the constant module algorithm, carrier recovery based on blind phase search with a sliding average of 4 and 16 test phases, and differential decoding to eliminate any cycle slips.

4. Results and discussions

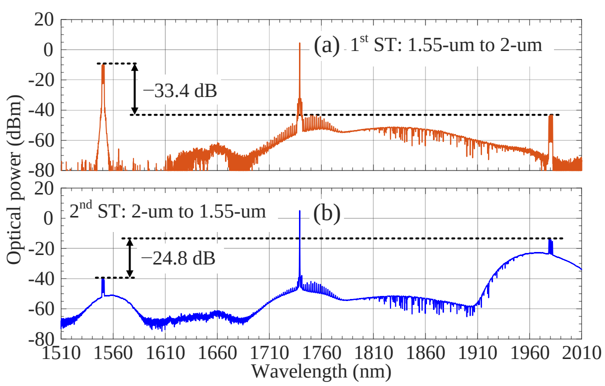

Fig. 4. Optical spectra of the two spectral translation stages.

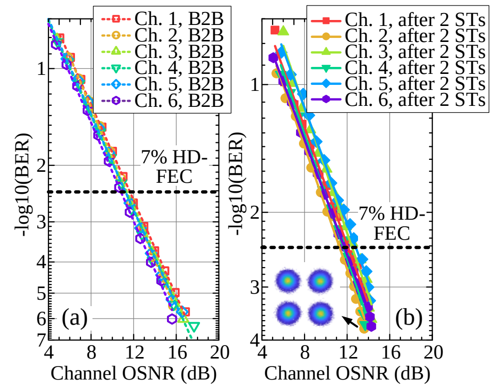

Fig. 5 BER performance of (a) the back-to-back signal, and (b) the signal after two spectral translation (ST) stages.

The two spectral translations are successful with an achievable OSNR per channel around 14 dB, and all 6 translated channels achieve BERs deeply below the FEC-limit, as shown in Fig. 5. Figure 5(a) shows the BER performance in the back-to-back case. The average OSNR sensitivity of the WDM signal is ~11 dB at the HD-FEC threshold (with 7% coding overhead, BER = 3.8×10^{-3}). Figure 5(b) shows the BER performance of the signal after the two ST stages. The average OSNR sensitivity for the 6 WDM channels is ~12.5 dB at the HD-FEC threshold, yielding an OSNR penalty of only ~1.5 dB. The inset of Fig. 5(b) shows the signal constellation map at a BER of 3×10^{-4}. A net rate of 358.8 Gbit/s is achieved after two spectral translation stages, assuming a 7% FEC overhead. The performance may be improved by improving the AlGaAsOI device in the first ST stage, replacing the optical couplers with dedicated WDM couplers for relevant bands to reduce the loss of the pump, using 2-µm-band filters to minimise the impact of ASE noise, and use a lower linewidth pump to eliminate the source of cycle slips.

5. Conclusion

We have proposed and successfully demonstrated the generation and coherent detection of 2-µm band signals by spectral translation. Using two highly nonlinear AlGaAsOI nanowaveguides and a TDFA based pump beam working at 1.74-µm, 6 WDM × 32 Gbaud QPSK channels have been successfully spectrally translated from the 1.55-µm to 2-µm band, and back again for coherent detection. All 6 WDM channels exhibit BER below the HD-FEC threshold, with an OSNR penalty of ~1.5 dB. This demonstration has the potential to support high spectral efficiency transmission in the 2-µm band using mature off-the-shelf devices operating in the 1.55-µm band.

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