Optical Signal Processing in Highly-Nonlinear Chalcogenide Planar Waveguides

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Abstract: Bit-error rate performance of newly developed As₂S₃ planar waveguides in applications of high-speed all-optical time-division demultiplexing and wavelength conversion of 40-160 Gb/s optical signals through the use of four-wave mixing and cross-phase modulation is investigated.

1. Introduction

Nonlinear optical phenomena can be applied in a variety of ways to enable a suite of all-optical signal processing functions for future high-speed and high-capacity optical communication networks. These include signal regeneration [1], time-division demultiplexing [2-6], wavelength conversion [7-10], phase conjugated/mid span spectrally-inverted transmission [11], parametric amplification, ultra-fast logic gating, buffering and switching. The all-optical nonlinear approach avoids the need for optical to electronic conversions and can therefore circumvent the bandwidth limitations and prohibitive cost and manufacturing complexity of high-speed opto-electronics. This grows more important as data modulation rates increase beyond current 40 Gb/s systems to 160 Gb/s. Nonlinear signal processing can be performed in various media such as optical fibre [1-3],[8],[9], semiconductor optical amplifiers [5] and periodically poled LiNbO₃ (PPLN) [6]. While speed of SOAs is ultimately limited by carrier recovery effects, optical fiber exploiting the $\chi^{(3)}$ nonlinearity through the third-order electric susceptibility that gives rise to the optical Kerr effect is near instantaneous and therefore well suited for high-speed signals. Optical fiber also has advantages of broadband low loss transmission and passive operation, not requiring feedback temperature control or electric biasing. On the other hand, while SOA and PPLN require device length on the order of centimetres, fiber based experiments originally using dispersion-shifted fibre (DSF) with nonlinearity coefficient of $3 \text{ W}^{-1}\text{km}^{-1}$ required kilometres of length to accumulate sufficient nonlinearity with moderate launch powers [2], which made for bulky devices sensitive to environmental perturbations. Development in late 1990's of highly nonlinear fibres with nonlinearity typically 3-7 times higher than DSF enabled shorter lengths of hundreds of metres [3]. Subsequent development of photonic structured fibres pushed the nonlinearity even higher toward $100 \text{ W}^{-1}\text{km}^{-1}$ [8]. Advances in non-silica based glass fibers exhibiting much higher n_2 coefficient dramatically increased fiber nonlinearity beyond another order of magnitude to $> 1000 \text{ W}^{-1}\text{km}^{-1}$, albeit with high loss, enabling signal processing with remarkably short lengths on the order of 1 m for both BiO₃ [1] and the chalcogenide, As-Se [9] fibers.

Beyond shorter fibre lengths, challenge remains for shrinking optical waveguides from discrete fiber devices onto a planar platform whereupon integration of multi-signal processing functions or parallel optical circuits for processing different wavelength signals simultaneously on a single photonic chip can be envisioned. It's development calls for both ultra-highly nonlinearity and low loss to ensure low operating power. Recent progress in silicon waveguides has demonstrated fabrication of sub-micron dimension photonic circuits i.e. nanowires enabling sufficient nonlinearity to be reached in centimetre lengths, albeit with quite high losses, for both all-optical wavelength conversion [7] and phase conjugation [11] at 10-40 Gb/s. However, silicon suffers significant nonlinear losses from free-carrier absorption and two-photon absorption (TPA) that may impede operation at higher bit rates.

In another approach, fabrication of chalcogenide planar rib waveguides based on As₂S₃ glass has been explored to take advantage of the material's ultra-high n_2 coefficient up to three orders of magnitude greater than silica, and low TPA to realize ultra-fast Kerr nonlinearity in compact photonic circuits suited to higher signal bit-rates. CUDOS has recently developed a variety of such waveguides exhibiting nonlinearity coefficient up to $2080 \text{ W}^{-1}\text{km}^{-1}$, with low polarization dependant and insertion losses. Such low losses have even been achieved in more complex circuits consisting of serpentine shaped rib waveguides as shown in Fig. 1 enabling nonlinearity to accumulate along longer lengths up to 22 cm in a compact 7 cm size chip [12]. Such high nonlinearity was achieved with comparatively broad mode area of $5-7 \text{ m}^2$ without complexity of nanowire fabrication. This leaves room for further nonlinearity enhancement through the shrinking of waveguides dimensions, which also provides means to tailor chromatic dispersion between normal to anomalous regions. The application of these waveguides to optical time-division demultiplexing [4] and wavelength conversion [10] at high bit-rates through use of four wave mixing (FWM) and cross phase modulation (XPM) respectively was explored for validating the bit-error rate performance.

The demultiplexing of a 160 Gb/s signal into its 10 Gb/s tributary channels used a 5 cm length As_2S_3 planar rib waveguide with mode area of $5.7 \text{ } \mu\text{m}^2$ for nonlinearity coefficient of $2080 \text{ W}^{-1}\text{km}^{-1}$. A 160 Gb/s signal at wavelength $\lambda_s = 1560 \text{ nm}$ was combined with a 10 GHz source of 1.5 ps pulses at wavelength $\lambda_p = 1550 \text{ nm}$ and launched into the waveguide. By FWM, each pump pulse of peak power 4.4 W coinciding with the signal pulse generated an idler pulse at new wavelength $\lambda_i = 2\lambda_p - \lambda_s = 1540 \text{ nm}$. Fig. 2(a) and (b) compare input and output spectra. The 10 Gb/s idler channel was extracted with a band-pass optical filter (BPF) to produce the clear output eye diagrams shown in Fig. 2(c). Bit error rate measurements showed low power penalty less than 1 dB for all sixteen 10 Gb/s channels.

Development of the longer 22 cm length As_2S_3 waveguide shown in Fig. 1 enabled all-optical wavelength conversion of 40-80 Gb/s signals. The input signal was co-launched into the waveguide with a cw laser tuned to the desired output wavelength. By XPM, the cw mode was nonlinearly phase modulated in proportion to the instantaneous co-propagating signal power, and the corresponding frequency modulated side-bands were optically filtered to obtain a replica of the input signal at the new wavelength. Fig. 2(d) shows the converted spectra for launching 80 Gb/s signal of 1.5 ps pulses at 1550 nm wavelength with average launch powers of 24 and 22 dBm for signal and cw respectively. In case of wavelength converting a 40 Gb/s input signal of 4.4 ps pulses, a BER power penalty of $\sim 1 \text{ dB}$ was achieved for wavelength conversion from 1535 to either 1555, 1560 or 1565 nm.

Extending application of the waveguides to other optical signal processing functions and higher bit-rates will be aided by further reduction of the input peak power requirements through fabrication advances enabling combination of either longer waveguides or smaller optical mode area, or improved materials for enhancing the nonlinearity coefficient, and to some extent, tailoring dispersion – all while maintaining low propagation losses.

Fig. 1. (a) Optical micrograph of 22 cm length As_2S_3 rib-waveguide cross-section. (b) Serpentine waveguide geometry

Fig. 2: (a) 160 Gb/s demultiplexing: input (b) output spectra and (c) optical eye diagrams. (d) 80 Gb/s wavelength conversion output spectra.

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