

Bi-directional spectral broadening measurements for accurate characterisation of nonlinear hybrid integrated waveguides

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Abstract. The emerging interest in integrated optical technologies raises the need for precise characterisation techniques for waveguides presenting nonlinearities. Here we propose a non-interferometric measurement to accurately characterise the Kerr contribution in hybrid waveguides and illustrate its performances using SiN waveguides with a GSS chalcogenide top-layer. The sensitivity of our technique in terms of nonlinear phase reaches 10 mrad and its accuracy makes possible to extract the nonlinear contributions from the top-layer.

1 Introduction

One of the interesting consequences of the strong light confinement in integrated waveguides is the emergence of nonlinear effects, even at low powers. In combination with large capabilities of dispersion engineering in integrated devices, these nonlinear effects lead to observation of various phenomena, such as optical Kerr frequency combs or super continuum generation. Their possible applications extend from spectroscopy to optical communication systems [1].

In order to overcome the limitations imposed by the properties of the most common integrated photonics materials, such as silicon and silicon nitride, hybrid waveguide structures are envisioned. They combine materials selected for their nonlinear properties and their potentialities in terms of hybridisation. The design of such hybrid structures with specific characteristics requires complete simulation tools and, on the other hand, raises the necessity for accurate characterisation methods enabling to verify the real performances of fabricated samples.

Characterisation methods dedicated to 3rd-order nonlinearities of integrated structures are mainly based on the analysis of spectral broadening due to the self-phase modulation (SPM) in pulsed regime or gain amplification of signal beam in the four-wave mixing process. One of the common issue for proper characterisations concerns the systematic measurements of the injected power in the waveguide.

Here we propose a bi-directional method based on the analysis of the spectral broadening of laser pulses with top-hat like spectral shape to improve the sensitivity in terms of nonlinear phase shift. It allows accurate (10 %) and reproducible characterisation of the waveguides in

terms of nonlinear index (n_2) and gives access to the comparison between different samples despite the variation in their related coupling efficiencies. Using the calculated field distribution in hybrid waveguides, the specific nonlinear contribution of the deposited layer can be extracted.

2 Proposed method

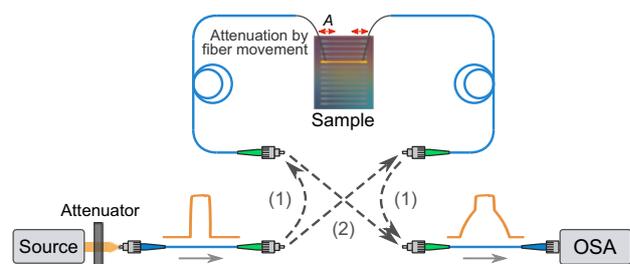


Figure 1. Experimental setup with the typical input and output spectra, and the fibre connections used to perform bi-directional measurements. The source is composed of an erbium-doped fibre laser followed by a grating based pulse shaper.

Our method is based on a previously reported D-Scan method [2]. Here, we present an evolution on the processing of the acquired optical spectra to improve the accuracy of the method in order to reveal the properties of hybrid waveguide structures. The principal scheme of the setup is shown in figure 1. An erbium-doped fiber laser with a grating-based optical filter (pulse shaper) are used as a source that delivers pulses with a top-hat like spectral shape without any residual chirp. Pulses are injected and collected through two cleaved polarisation maintaining (PM) fibres aligned above grating couplers engraved at each waveguide extremity. Self-phase modulation in

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the waveguide leads to spectral broadening and creates observable ‘nonlinear’ wings as illustrated in figure 1. Neglecting the chromatic dispersion and other nonlinear effects (verified in practice), the introduced nonlinear phase can be then retrieved by simulating the propagation of the initial pulses through a nonlinear waveguide.

The correct restitution of the results for nonlinear measurements implies the exact peak power in the waveguide to be known. As the coupling efficiencies may not be symmetric at the two waveguide extremities, we perform bi-directional measurements using PM fibres in order to reverse the coupling direction without modifying any position in the injection set-up. Furthermore, one has to take into account for the nonlinear phase shift introduced by the PM fibres. The separation between the nonlinear contributions of the PM fibres and the waveguide is done by varying independently the incident power set by the attenuator (see fig. 1) and the waveguide coupling efficiency achieved by shifting the fibre position along the diffraction grating (introducing an attenuation factor A).

3 Results and Discussion

Our method has been applied to characterise 3 samples of SiN_x waveguides without and with a top-layer cladding of chalcogenide glass (GeSbS, GSS) with a thickness of 100 nm and 150 nm. The waveguides have been designed to support one single mode in quasi-TE configuration (fig. 2). The studied waveguides include straight and spi-

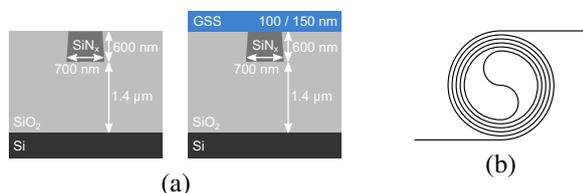


Figure 2. Cross section of studied waveguides (a). Example of a spiral shaped waveguide used for characterisation (b).

ral geometries with minimal radius of $30\ \mu\text{m}$ and lengths varying from 3.5 mm to 12.9 mm.

The bi-directional measurements have been performed for 7 waveguides on each sample, for 5 different input powers (set with the attenuator) and 6 different coupling efficiencies between the fibre and the waveguide. The contributions of the fibre and the waveguide to the nonlinear phase are extracted using optimisation of the nonlinear phases in a numerical simulation so that it fits the experimental data. The simulation takes into account the SPM effect only, as the chirp introduced by the second-order dispersion effects in the injection fibers and the waveguide are negligible. The spectrum at the minimal power (presenting no wings) is used as a reference spectrum at the input for the simulation and the ratio between the power in the nonlinear wings and the power in the central part serves as the optimisation criteria (see insight in figure 3). The dependency of this ratio with the injected power in waveguides is shown in the figure 3. It demonstrates a

good agreement between the numerical simulation and the experimental data. It allows us to retrieve the nonlinear phases accumulated in the fibres and in the waveguides and, using the known linear loss, the effective nonlinear coefficients γ for the waveguides under study. Respect to SiN waveguides, an improvement by more than a factor of 2 of the nonlinear coefficient γ is demonstrated with the hybrid SiN -GSS waveguides.

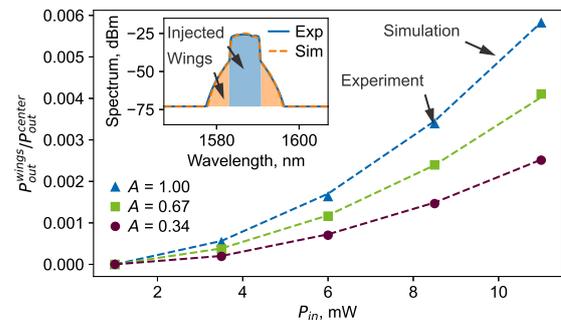


Figure 3. Variation of the ratio between the power in the wings and in the central part of the spectrum with the input power and for three different coupling efficiencies.

Using the effective mode area calculated with Lumerical MODE and the linear loss, estimated from the insertion loss variation with the waveguide lengths, we get access to the effective nonlinear indices for all the samples. The knowledge of the field distribution in the different layers of our samples (also obtained using Lumerical MODE) gives access to the contribution, and though, the nonlinear refractive index of each material, respectively equal to $n_2 = (4.4 \pm 0.6) \cdot 10^{-19}\ \text{m}^2/\text{W}$ for SiN_x and $n_2 = (4.1 \pm 1.2) \cdot 10^{-18}\ \text{m}^2/\text{W}$ for GSS. These values are in agreement with those previously reported for SiN_x [3] and GSS [4].

4 Conclusion

We have shown the capacity of our method to characterise hybrid waveguides and extract the nonlinear contributions of the different materials. Details about the parameters extraction procedure and their uncertainties will be presented. Our method presents the advantage of a non-interferometric configuration that can be implemented with fully commercialised components and instruments.

References

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