Kerr effect enhancement through hybrid integration of 2D materials on the silicon platform

Student Paper

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ABSTRACT

2D materials such as graphene or transition metal dichalgogenide (TMD) have shown impressive performances in terms of second- and third-order non linearities. Hence, 2D materials have recently attracted attention for nonlinear applications, especially in the silicon platform where nonlinear effects are usually limited. However, this interest has raised numerous questions concerning the integration and applications that could follow. Here we present results of early investigations into the design of waveguides for the 2D material hybrid integration in the silicon platform. The work is focused on designing waveguides with strong effective permittivity and anomalous dispersion allowing the deposition of 2D materials. The engineering of the dispersion profile and the study of the transverse mode profile are performed for this goal.

Keywords: Nonlinear optics, 2D materials, silicon photonics, dispersion engineering.

1 INTRODUCTION

In the past few years, the silicon photonics community has been increasingly considering nonlinear optics (NLO) but has met a few difficulties due to the properties of materials used on this platform [1]. The catalog of traditional semiconductor or dielectric materials for the realization of optical waveguides and circuits is quite limited; in the end, silicon and silicon nitride are the main core materials, with silica as the low index material. Silicon is itself a very non-linear material (Kerr index $n_2 \simeq 5 \times 10^{-18} m^2 W^{-1}$) However, at telecom wavelengths, the efficiency of the nonlinear effect in silicon is seriously hampered by the two-photon absorption (TPA) mechanism [2]. On the other hand, silicon nitride provides an acceptable compromise, as it is free of TPA, but has a third order effect that is about 30 times lower than silicon. Impressive demonstrations of supercontinuum or frequency comb generation have been carried out and published on this Si_3N_4/SiO_2 platform in recent years. Yet, the inherent properties of the Si_3N_4 material lead to high threshold powers for the exploitation of non-linear effects, and a lack of miniaturization of waveguides and optical resonators, in other words a lack of integration. In this context, it is crucial to develop innovative approaches for enhancing non-linear effects in the silicon platform by combining new active materials with the planar structures of silicon photonics. As such, there is a wide range of innovative materials, especially 2D, to be associated with CMOS photonics. In order to achieve devices with low loss and high parametric gain, a solution is to proceed to the hybrid integration of 2D materials on the samples. 2D materials have showed incredible results and have already demonstrated good performances in term of nonlinear properties [3], [4]. The propagating or confined fields inside devices can benefit from the properties of this layer. These breakthroughs may improve the performances of third-order nonlinear phenomena in straight waveguides for the realization of parametric amplification and for the generation of super continuum emission, even if it is still difficult at this stage to anticipate all the other possible contributions of such an approach.

2 NONLINEAR WAVEGUIDE

2.1 Four Wave Mixing (FWM)

For the generation of supercontinuum and Kerr frequency combs, the nonlinear effect used is the Four Wave Mixing (FWM). It is a frequency conversion between one or two pump beams and two other frequencies called signal and idler. This energy transfer obeys to the conservation of energy and momentum, respectively, as follows:

$$\begin{cases} \omega_{P1} + \omega_{P2} = \omega_i + \omega_s \\ \beta_{P1} + \beta_{P2} = \beta_i + \beta_s \end{cases} \tag{1}$$

The efficiency of this nonlinear process increases as we get closer to the phase matching conditions. Thus, we have the following expression for the phase matching conditions.

$$\Delta\phi = \Delta\beta_L + \Delta\beta_{NL} = 0 \tag{2}$$

$$
\begin{cases} \Delta\beta_L = \sum_{k=0}^{\infty} \frac{1}{k!}\beta_k(\omega-\omega_P)^k \\ \Delta\beta_{NL} = 2\gamma P_{in} \end{cases}
$$

Where P_{in} is the pump power inside the waveguide and γ is the non linear coefficient.

2.2 Effective permittivity tensor

The nonlinear coefficient γ depends solely on the materials in the case of a bulk device. However, when considering an integrated waveguide using different materials showing different nonlinearities, it is necessary to consider the transverse distribution of the mode and take into account the contribution of different materials in order to derive the effective permittivity tensor [2] :

$$
\Gamma = \frac{A_0 \int_{A_0} e^*(r_\perp;\omega)\chi^{(3)}_{eff} e(r_\perp;\omega)e^*(r_\perp;\omega)e(r_\perp;\omega)dA}{(\int_{A_\infty} n^2(r_\perp)|e(r_\perp;\omega)|^2 dA)^2} \tag{3}
$$

The nonlinear coefficient can then directly be extracted using the following expression :

$$
\gamma = \frac{3\omega\Gamma}{4\epsilon_0 A_0 v_g^2} \tag{4}
$$

From Eq. (3) and Eq. (4) it follows that optimizing the overlap between the optical mode and the 2D material is critical to maximize the nonlinear coefficient of the hybrid waveguide. The monoatomic thickness of the 2D material brings some specific challenges on the optimization of this overlap, mainly in terms of maximum attainable light-matter interaction and proper design and simulation of the structure. Moreover, it has been reported that only the transverse-electric (TE) polarized mode is capable to efficiently exploit the nonlinear effect of the 2D materials [5].

2.3 Dispersion engineering

Due to the optogeometrical properties of the hybrid 2D-material/Si or Si_3N_4 waveguide, its propagation constant is strongly linked to the design and materials selected. A Taylor expansion of this propagation constant around the frequency of the pump allows us to derive the different factors that govern the propagation constant:

$$
\beta(\omega) = n(\omega)\frac{\omega}{c} = \sum_{k=0}^{\infty} \frac{1}{k!}(\omega-\omega_P)^k \left(\frac{d\beta}{d\omega}\right)^k_{\omega=\omega_P} \qquad (k = 1, 2, 3, ...) \tag{5}
$$

The second order of this expansion corresponds to the group velocity dispersion (GVD) and is the most critical parameter to consider when designing the dispersion of a waveguide for nonlinear applications. Indeed, as described earlier, in order to obtain the phase matching conditions, it is necessary to have $\beta_2 < 0$ where β_2 is the second order term of the Taylor expansion. This corresponds to the so called anomalous dispersion regime which is beneficial for most process using FWM.

3 PRELIMINARY RESULTS

The main goal is to select the proper kind of waveguides which is the best compromise between a good dispersion profile and an effective permittivity tensor that is much improved compared to a regular waveguide without a 2D material. This study has been conducted having the fabrication process in mind. Thus we need to check multiple conditions like the necessity to have a surface suitable for the deposition of 2D material and also, as we described earlier, an anomalous dispersion profile. We are considering here that the enhancement can be characterized in terms of overlap between the 2D material and the mode since the nonlinear contribution of a 2D sheet on a waveguide is not yet well understood (important discrepancies between theoretical and experimental results have been reported in [6]).

At the present stage of our investigation, we found that the best compromise between a strong overlap of the mode with the 2D material and an anomalous dispersion profile is a buried strip waveguide with silica cladding. The silica cladding is planarized, as schematically shown in Fig. 1(a), in order to bring the 2D material close to the waveguide core and ease its deposition. Thus, this waveguide has been preferentially considered for optimization with a full-vectorial mode solver. The 2D material was considered in a commercial Finite Difference Eigenmode (FDE) as a 2D conductive sheet [7] acting as a boundary condition for the mode distribution calculation. However, for the calculation of the permittivity tensor and overlap between the mode and the 2D material, the 2D sheet is considered with its effective thickness h_{eff}. Looking at results, we need first of all to point out that the dispersion profile of the waveguide seems not to be affected much by the deposition of a 2D sheet on top (figure 1 b). Using the modal distribution (Fig. 1(c)) we can then recover other informations like the overlap between the mode and the 2D material which is critical information since this is a parameter that needs to be optimized. For the device presented in figure 1, the overlap is $0,0560\%$ for a covered composite waveguide. As can be seen Fig. 1(d), the mode is slightly attracted by the 2D sheet but the effect remains very weak.

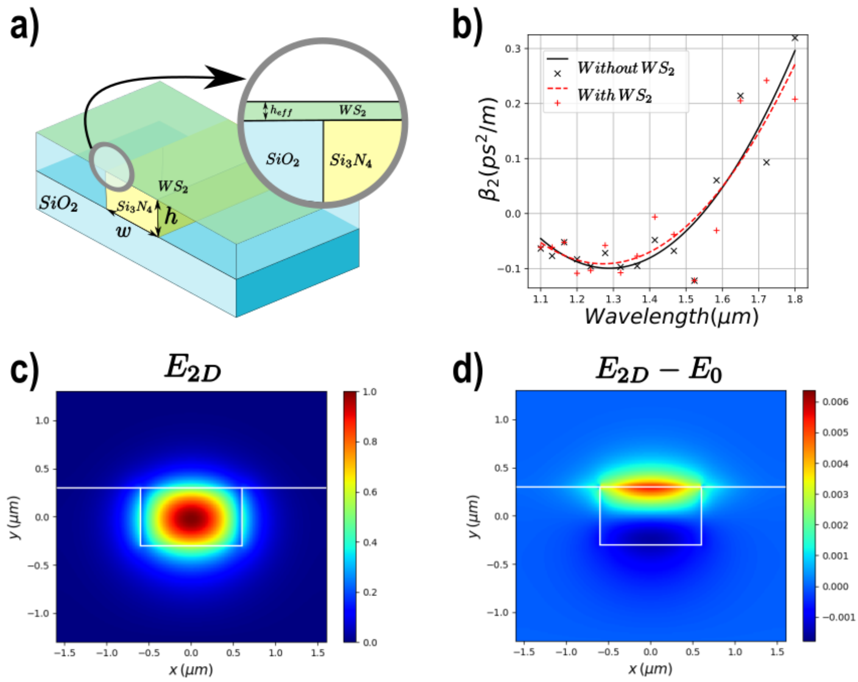

Figure 1. Study of the hybrid integration of 2D materials in Si_3N_4 core waveguides. a) Diagram showing the integration principle scheme. b) Comparison of the group velocity dispersion between a waveguide covered with a 2D sheet of WS_2 and a waveguide left without hybridization. The waveguide parameters are: 600 nm height and 1200 nm width c) Transverse mode distribution E_{2D} of the waveguide covered with WS_2 for a pump wavelength of 1550 nm. d) Difference between the TE transverse mode distribution of the covered waveguide E_{2D} and the TE transverse mode distribution of a waveguide left without hybridization E_0.

4 CONCLUSION

The fascinating nonlinear properties of 2D materials can be exploited by combining these outstanding materials (graphene, MoS_2, WS_2, etc.) with dielectric waveguides with a silicon or silicon nitride core. Such composite waveguides form the necessary basis for the possible demonstration of various physical effects (supercontinuum, frequency combs, etc) and for the realization of various functions and applications, in particular the realization of sources for communications, metrology, and spectroscopy on a chip. An important prerequisite, however, is to understand the properties of these materials when deposited on silicon or Si_3N_4, to identify the influence of free carriers on their optical properties, and to bring the studied configurations to convincing demonstrations of significant added value relative to more classical waveguide configurations. Our work explores this preliminary phase of nonlinear composite waveguides. We will report at the conference our latest simulation and experimental results.

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