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Published in:

DOI:
10.1109/JSTQE.2015.2490550

Publication date:
2016

Document Version:
Final published version

Citation for published version (APA):
Opportunities for wideband wavelength conversion in foundry-compatible silicon waveguides covered with graphene

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Abstract—We numerically examine the opportunities for wideband wavelength conversion through four-wave mixing (FWM) in a foundry-compatible 220 nm-thick silicon-on-insulator (SOI) waveguide covered with the highly nonlinear two-dimensional material of graphene. As a case study, we consider a foundry-compatible SOI waveguide shaped as a double spiral and covered with two separate graphene sheets, which are covered in turn by two solid polymer electrolyte gates. When combining sub-watt level pump powers with a short waveguide length of only a few hundreds of microns, ‘perfectly phase-matched’ conversion with significant efficiencies close to −20 dB can be obtained over a more than 40 THz-wide signal band adjacent to the pump frequency. Because of the tunability of the graphene properties using the electrolyte top gates, it is also possible to obtain ‘quasi-phase matched’ FWM conversion through a periodic sign reversal of the graphene third-order nonlinearity along the waveguide. Conversion efficiencies exceeding −30 dB can be achieved over a 3.4 THz-wide signal band that is situated as much as 58 THz away from the pump frequency. Finally, the tunability of the graphene also allows for switching the converter from the perfectly phase-matched to the quasi-phase-matched operation mode.

Index Terms—Integrated optics, nonlinear wave propagation, phase matching, silicon on insulator technology, thin film devices, waveguide components

I. INTRODUCTION

ONLINEAR optical wavelength conversion, a research area which emerged together with the invention of the laser in 1960, continues to be widely investigated today with a broad range of application possibilities in spectroscopy, metrology, optical telecommunications, and a host of other fields [1]. Over the past decade much attention has been paid to the development of waveguide-based nonlinear optical wavelength converters that can be embedded in photonic integrated circuits [2]-[17]. The process most often employed in these devices is the third-order nonlinear interaction of Kerr four-wave mixing (FWM), which entails the conversion of a signal input frequency $\nu_s$ to an idler output frequency $\nu_i$ in the presence of a pump at frequency $\nu_p$ with $\nu_p - \nu_s = \nu_i - \nu_g$. Various waveguide converters have already been demonstrated, several of which have been implemented in the silicon-on-insulator (SOI) material platform allowing for strong light confinement and high-precision manufacturing using the mature CMOS technology [1].

When targeting efficient FWM conversion over a wide range of signal wavelengths, wideband phase matching is required. This is quite challenging in SOI waveguides because of silicon’s strong material dispersion [4]. One approach to tackle this problem is to engineer the cross-sectional dimensions, and hence the dispersion, of SOI waveguides to establish (almost) perfect phase matching (PPM) over a wide continuous signal frequency band adjacent to the pump frequency. Turner and co-workers succeeded in designing an SOI waveguide exhibiting dispersion-engineered PPM over a broad pump-to-signal bandwidth of 52 THz in the near-infrared telecom domain [11]. However, the waveguide had to be made as long as 1.5 cm to attain significant conversion efficiencies around −20 dB at a pump input power of 110 mW. Such waveguide lengths result in large device footprints of minimally 10000 µm². The required length could be somewhat reduced to sub-cm-values when suppressing the free carrier absorption in the waveguide by means of carrier-extracting p-i-n diodes. Nevertheless, the particular SOI waveguide developed by Turner et al. [11] exhibits another drawback: Its highly customized cross-section does not comply with the fabrication constraints of multi-project-wafer-oriented silicon photonics foundries, which employ a standard waveguide thickness of 220 nm [18]. Since the use of such foundries can pave the way to the large-volume fabrication of integrated photonic components at low cost [1], adhering to these foundry standards is a natural strategy to exploit the full potential of silicon photonic devices.

Moving from the customized SOI waveguide as discussed above [11] to foundry-compatible 220 nm-thick SOI waveguides does not have a strong influence on the required propagation length for efficient conversion, but it inevitably reduces the achievable PPM bandwidth [8]. However, it is possible to extend the wavelength range of phase-matched FWM outside the PPM bandwidth using the concept of quasi-phase-matching (QPM). When employing QPM for a given set of pump, signal and idler wavelengths, the phase mismatch for the considered set of wavelengths is periodically compensated by varying the waveguide’s optical properties along the propagation path. Different schemes for QPM of FWM processes in silicon waveguides were recently introduced, including QPM based on an adiabatic variation of the dispersion along an SOI waveguide [15] - [17], and ‘automatic’ QPM where the
anisotropy of silicon’s Kerr tensor is exploited to induce a spatially varying Kerr nonlinearity for Transverse Electric (TE) modes propagating along a uniform SOI ring or spiral [12]-[13]. These QPM schemes can be implemented while also allowing PPM conversion around the pump frequency [13] - [16], albeit with a small yet distinguishable penalty in PPM conversion efficiency. This penalty is induced by the spatial waveguide variations required for QPM, yielding less efficient PPM conversion than possible with uniform waveguide properties optimized for PPM all along the propagation path. More importantly, the efficiency of these QPM conversion schemes is less than optimal in that none of them achieve the ‘ideal’, most effective scenario where the third-order FWM nonlinearity periodically reverses sign along the waveguide, in analogy with periodically poled second-order nonlinear media [19]. As such, the existing QPM schemes for FWM processes in silicon waveguides are in fact not optimal when targeting wideband yet efficient wavelength conversion in foundry-compatible 220 nm-thick SOI waveguides with preferably a short propagation length.

In this paper, we numerically examine the opportunities for wideband wavelength conversion in a foundry-compatible 220 nm-thick SOI waveguide combined with the highly nonlinear two-dimensional material of graphene. When limiting the waveguide length to a few hundreds of microns to enable a small device footprint, we find that the deposition of a graphene top layer on the SOI waveguide leads to a significant conversion efficiency improvement in the PPM regime. Furthermore, the graphene deposition enables a new scheme for establishing QPM. Indeed, because of the tunability of the graphene properties through control of its chemical potential $\mu$, it is possible to periodically reverse the sign of the effective FWM nonlinearity experienced by the TE waveguide modes along their propagation path, enabling for the first time QPM of FWM processes employing the ‘ideal’ and most effective scenario. The tunability of the top layer also allows for reconfiguration between the PPM and QPM conversion modes, so that both can be realized within the same waveguide without a penalty in PPM conversion efficiency. As a case study, we numerically simulate the wavelength conversion performance of a spiral-shaped graphene-covered foundry-compatible SOI waveguide in both the PPM and QPM regimes, and compare it with the performance attainable in the bare SOI waveguide.

This paper is organized as follows: In Section II, we address the basic concepts of PPM and QPM wavelength conversion in SOI waveguides covered with graphene. In Section III, we discuss the design of a spiral-shaped graphene-covered foundry-compatible SOI waveguide allowing both PPM and QPM conversion, and evaluate its performance in the PPM regime (Section III.A) and the QPM regime (Section III.B). Finally, we conclude in Section IV.

II. BASIC CONCEPTS OF PPM AND QPM WAVELENGTH CONVERSION IN GRAPHENE-COVERED SOI WAVEGUIDES

The spatial evolution of the pump, signal and idler fields at frequencies $\nu_{p/s/i}$ or wavelengths $\lambda_{p/s/i}$ in a graphene-covered SOI waveguide converter is governed by nonlinear propagation equations that describe Kerr-nonlinear interactions, including not only the FWM conversion process but also Kerr-induced phase modulation. We exclude Raman-nonlinear interactions since we can assume that the FWM transitions are detuned far away from the Raman resonances of graphene [20]. Furthermore, we focus on (quasi-) continuous-wave operation in the strong-pump approximation [21], and assume all fields to be TE polarized. Thus, the polarization of the fields is within the plane of the graphene top layer; having out-of-plane field components would not be beneficial for the FWM efficiency, since the Kerr tensor elements of graphene are considered negligible for the polarization direction perpendicular to the graphene sheet [22]. Finally, although a graphene-covered SOI waveguide is a heterogeneous medium, we will describe the fields in the same way as those in a homogeneous waveguide and introduce effective waveguide parameters (see Appendix) to take into account the medium’s hybrid structure. As such, we can use the following set of generic equations for describing the steady-state spatial evolution of the slowly varying pump, signal, and idler field amplitudes $A_p(\zeta), A_s(\zeta), A_i(\zeta)$ [12], [21], [23]:

$$\frac{\partial A_p}{\partial \zeta} = i\gamma_p |A_p|^2 A_p - \alpha_p A_p - \left(\frac{\omega_p}{\omega_p}\right)^2 \left(\frac{|FCA|}{2} - i\frac{\omega_p}{c} FCI\right) NA_p$$  \hspace{1cm} (1)

$$\frac{\partial A_s}{\partial \zeta} = i\gamma_{C1} |A_p|^2 A_s + i\gamma_{M1} A_p^2 A_i^* e^{-i\Delta k \zeta} - \alpha_s A_s$$

$$\frac{\partial A_i}{\partial \zeta} = i\gamma_{C2} |A_p|^2 A_i + i\gamma_{M2} A_p^2 A_s^* e^{-i\Delta k \zeta} - \alpha_i A_i$$

where $\zeta$ is the spatial coordinate along the waveguide, and where $A_{p/s/i}(\zeta)$ are normalized such that $|A_{p/s/i}(\zeta)|^2$ corresponds to power. The FWM terms are those that contain both the linear phase mismatch $\Delta k = -2k_p + k_s + k_i$ (with $k_{p/s/i}$ being the pump, signal and idler wave numbers), and the effective coefficients $\gamma_{M1/M2} = \gamma_{M1 Si/M2 Si} + \gamma_{M1 g/M2 g}$, comprising contributions from the SOI waveguide and the graphene sheet. In Eq. (1) the effective coefficient $\gamma_{S}$ contains $\gamma_{S,Si}$ accounting for self-phase modulation and two-photon absorption at the pump wavelength in the SOI waveguide, and also comprises $\gamma_{S,g}$ capturing the corresponding phenomena in the graphene layer. In Eqs. (2)-(3) the effective coefficients $\gamma_{C1/C2}$ consist of $\gamma_{C1 Si/C2 Si}$ covering cross-phase modulation and cross-two-photon absorption in the SOI waveguide for pump/signal and pump/idler photons, respectively, and also comprise $\gamma_{C1 g/C2 g}$ representing the equivalent effects in the graphene. The factors $\alpha_{p/s/i} = \alpha_{p,Si/Si,Si} + \alpha_{p,g/Si,g}$ account for the linear losses in the SOI waveguide and the graphene sheet. The formulas for all these effective parameters can be found in Appendix. We remark that they all are function
of the spatial coordinate $\zeta$, as is required for QPM operation and will be discussed in detail in the next section. The last term in Eqs. (1)-(3) represents free-carrier effects with $\sigma_{\text{PCA}}$ and $\sigma_{\text{FCI}}$ coefficients quantifying the efficiency of free-carrier absorption and free-carrier index change, respectively [9], and with $\omega_0/\nu_0 = 2\pi/\nu_0/\nu_i$ and $\omega_0 = 2\pi c/(1550 \text{ nm})$ where $c$ indicates the speed of light. The factor $N$ in this term is the effective free-carrier density in the waveguide:

$$N = \frac{\tau_{\text{eff}}}{2h\nu_p A} \left( \text{Im}(2\gamma_{S,i}) + r_D \text{Im}(2\gamma_{S,g}) \right) |A_p|^4$$

$$+ \frac{\tau_{\text{eff}}r_D}{h\nu_p A^2} \times \left( 2\alpha_{p,g}|A_p|^2 + 2\alpha_{s,g}|A_s|^2 \frac{\nu_p}{\nu_s} + 2\alpha_{r,g}|A_i|^2 \frac{\nu_p}{\nu_i} \right) \quad (4)$$

with $h$ Planck’s constant. The first term at the right-hand side of Eq. (4) represents the free-carrier generation induced by two-photon absorption in the SOI waveguide and the cor- responding absorption contribution in the graphene top layer, and the second term indicates the free-carrier generation induced by one-photon absorption in the graphene layer only. The graphene contribution to these two terms has been expressed in a rather phenomenological way since not all photons absorbed in the graphene sheet give rise to the creation of free carriers and instead can contribute to, amongst others, intra-band transitions. The factor $\tau_{\text{eff}}$ in Eq. (4) indicates the effective free-carrier lifetime. Because of the short free-carrier lifetime in graphene, only the graphene-generated free carriers that diffuse into the silicon waveguide will effectively contribute to the free-carrier effects, as shown earlier [24]. As such, in our numerical simulations we are allowed to employ the values for $\tau_{\text{eff}}$, $\sigma_{\text{PCA}}$ and $\sigma_{\text{FCI}}$ of the bare SOI waveguide, and incorporate the contribution from the graphene-generated free carriers by including a graphene-to-SOI diffusion ratio $r_D$ in Eq. (4). This ratio quantifies the fraction of the free carriers generated in the graphene that diffuses into the SOI waveguide. Finally, the factor $A'$ in Eq. (4) represents the waveguide cross-sectional area over which the free carriers are distributed.

Turning now to the FWM terms in Eqs. (1)-(3), both the linear phase mismatch $\Delta k = -2k_p + k_s + k_i$ and the nonlinear phase mismatch contribution, function of $\text{Re}(\gamma_S)$ and the pump power $P_p$, need to be added up to obtain the full phase mismatch $\Delta k_{\text{total}}$. Using a Taylor series expansion for the linear contribution, $\Delta k_{\text{total}}$ can be expressed as

$$\Delta k_{\text{total}} = \beta_2 \Delta \omega_{ps}^2 + (1/12)\beta_4 \Delta \omega_{ps}^4 + 2\text{Re}(\gamma_S)P_p \quad (5)$$

with $\beta_i$ representing the $i$-th order dispersion at the pump wavelength and with $\Delta \omega_{ps} = 2\pi(\nu_s - \nu_p)$. Taking into account that the second-order dispersion term generally dominates over the fourth-order dispersion term, one can engineer $\beta_2$ to obtain PPM (i.e. $\Delta k_{\text{total}} \approx 0$) within a certain operation bandwidth in the vicinity of the pump frequency $\nu_p$. As the evolution of the idler power $|A_i|^2$ with position $\zeta$ depends on the phase mismatch along the expression

$$|A_i|^2/\partial \zeta \propto \cos(-\Delta k_{\text{total}} \zeta),$$

the idler experiences a continuous power growth in the PPM regime along the waveguide, and no phase-mismatch-induced transition from idler growth to idler depletion can occur.

Outside the PPM operation bandwidth, the phase mismatch $\Delta k_{\text{total}}$ can deviate significantly from zero due to the fourth-order dispersion term in Eq. (5), inducing a change in the fields’ phase relation so that the term $\cos(-\Delta k_{\text{total}} \zeta)$ determining the idler power evolution will periodically evolve along the waveguide from $\cos(0) = 1$ to $\cos(\pi) = -1$ and back. As a result, there will be a reversal of the conversion process with idler photons being annihilated, deteriorating the net idler growth. The latter can be overcome by employing QPM, so that for a discrete set of signal and idler frequencies very far away from the pump frequency one can also attain an efficient idler growth. Generally speaking, QPM aims at periodi-cally compensating the phase-mismatch-induced change in the fields’ phase relation while avoiding the detrimental reversal of the conversion process, so that an overall efficient growth of the idler power is achieved [12]. Ideally, in the sections where the sign of $\cos(-\Delta k_{\text{total}} \zeta)$ has changed, one should also have a sign reversal in the Kerr nonlinearity, so that both sign changes annihilate each other and the idler continues to grow.

As mentioned, the different effective coefficients in Eqs. (1)-(3) take into account the contributions from both the SOI waveguide and the graphene top layer. The impact of the latter on both the loss parameters and the nonlinear parameters can be very strong. Experimental investigations with isolated graphene at photon energies above the one-photon absorption onset (i.e. $h\nu > 2|\mu|$) have revealed extremely high values for the nonlinearity of the two-dimensional material [26] - [28]. Our recent calculations indicate that, when the chemical potential $\mu$ is tuned such that the photon energy is just below the onset of one-photon absorption, the nonlinearities also become very strong due to the presence of a resonance peak [22], [29]. This is not surprising, since conventional semiconductors also exhibit strong nonlinearity just below the threshold for single photon absorption [30]. This implies that the strong nonlinearity enhancement reported in [27] upon graphene deposition on a silicon waveguide can be combined with low linear absorption losses, favoring efficient PPM conversion. In addition, when moving from the one-photon to the two-photon absorption threshold a sign change occurs in the graphene nonlinearities, which is also in line with the behavior of the nonlinearities of direct-bandgap semiconductors [30]. For fixed photon energies this sign change can be controlled by changing $\mu$. Hence, by spatially varying the chemical potential $\mu$ of a graphene layer on top of an SOI waveguide using, e.g., locally deposited electrolyte gates, it should be possible to establish QPM conversion along the ‘ideal’ scheme where the nonlinearity periodically reverses sign along the propagation path. What is more, because of the voltage-tunability of graphene, one is also able to switch from the PPM conversion mode with a uniform, maximum

1As shown earlier [16], [25], the idler evolution is not merely determined by $\Delta k$ as one might expect from Eq. (3), but by $\Delta k_{\text{total}}$ in which also the phase modulation effects are incorporated.
Fig. 1. Basic concept of the graphene-covered spiral-shaped SOI waveguide converter with (a) PPM operation and (b) QPM operation. The upper and lower spiral halves are covered with two separate graphene sheets. These graphene sheets are covered in turn with solid polymer electrolyte gates, indicated as the green-colored, dark-shaded area ('gate 1') and red-colored, light-shaded area ('gate 2'). These two electrolyte gates are also separated by a small spacing. On top of each gate and on its underlying graphene sheet electrical contacts are placed, across which a voltage is applied to tune the graphene properties. By applying either the same or different bias voltages to the two gates, the optical fields propagating in the spiral waveguide experience either a constant high graphene nonlinearity along the spiral path as desired for PPM operation, or a graphene nonlinearity with periodically changing sign along the spiral as required for QPM operation. Neither PPM nor QPM operation will be affected by the spacing between the two graphene sheets as long as it is kept below a few micron, which is very well feasible using, e.g., photolithographic graphene patterning [32]. The particular converter design sketched in Fig. 1 offers several practical advantages: While the use of a spiral waveguide enables a small device footprint, the large-area gate patterning on top is less prone to fabrication errors than when depositing individual gates on each spiral section separately. As well, the solid polymer electrolyte gates made of, e.g., LiClO$_4$ and Poly(ethylene) Oxide (PEO) allow tuning the chemical potential of graphene to very high values using only low voltages (e.g., $|\mu| > 0.8$ eV using a voltage of only 3 V [31]), and can nowadays be patterned with submicron accuracy [33]. Another important asset of the spiral design is that in the QPM regime the periodicity of the positive nonlinear and negative nonlinear waveguide sections is chirped. As is the case for broadband second-harmonic generation in chirped periodically poled nonlinear media [19], we find here that this converter design allows QPM operation not just for one discrete signal wavelength far away from the pump wavelength, but for a continuous band of signal wavelengths, hence enabling truly wideband conversion.

In what follows we will determine the design parameters of the targeted graphene-covered SOI waveguide converter. To find the optimal values for the graphene chemical potential $|\mu|$, we will use graphs generated with our earlier presented theory [22], [29] for both the linear and nonlinear conductivities of graphene. This way we can determine at which $|\mu|$-values we have both low linear absorption and strong nonlinear effects. Our theoretical curves for the linear conductivity are in line with experimental data and with the widely used Kubo-formalism (see, e.g., Supplementary Information of [27]), so that we can directly implement these theoretical data in our numerical simulations for the converter. In contrast, the theoretical curves for the nonlinear conductivity are systematically lower than what has been experimentally observed.
[22], [29], so we take them only as a qualitative guide. We use them only to estimate at which values of $|\bar{\mu}|$ with low linear absorption we can expect nonlinearities as strong as those observed experimentally at $|\bar{\mu}|$-values where the linear absorption was high. We then take these values of $|\bar{\mu}|$ with small linear absorption as our working point, and implement the experimentally determined values of the nonlinearity in our numerical simulations.

III. DESIGN AND MODELING RESULTS FOR THE SPIRAL-SHAPED FOUNDRY-COMPATIBLE SOI WAVEGUIDE CONVERTER COVERED WITH GRAPHENE

A. PPM conversion

We first investigate the optimal graphene properties for PPM conversion. The two gates in Fig. 1 should be subjected to the same bias voltage $U_{PPM}$, or, in other words, all graphene sections should be tuned to the same chemical potential $\mu_{PPM}$. This chemical potential should be chosen such that the corresponding graphene nonlinearity is high and the linear absorption loss is low. As PPM conversion occurs between pump, signal and idler wavelengths that lie relatively close to each other, the nonlinearity $\sigma^{(3)}(-\omega_s, \omega_p, \omega_p)$ for FWM between the pump, signal and idler can be approximated by the nonlinearity for self-phase modulation at the pump wavelength. When assuming a telecom pump wavelength $\lambda_p$ of 1625 nm (this corresponds to a photon energy of 0.763 eV) and a conservative carrier scattering rate of 33 meV for both inter- and intra-band scattering in graphene, our earlier presented theory [22], [29] predicts that the graphene linear conductivity $\sigma^{(1)}(\omega_p)$ and its third-order conductivity for self-phase modulation $\text{Im} (\sigma^{(3)}(-\omega_p, \omega_p, \omega_p))$ will vary with the chemical potential as shown in Figs. 2 and 3. We point out that the relation between these conductivities and their corresponding bulk susceptibilities is given by $\chi = \sigma / (-i \omega \epsilon_0 d_0)$ with $\epsilon_0$ the dielectric permittivity and $d_0 = 0.3$ nm the effective thickness of graphene. Fig. 2 for the linear conductivity shows that, at $|\bar{\mu}| > 0.763$ eV, for which the considered pump photon energy is below the one-photon absorption threshold, the one-photon absorption loss quantified by $\text{Re} (\sigma^{(1)})$ decreases from the universal conductivity $\sigma_0$ to values far below $\sigma_0$. In this region one no longer has absorption associated with interband transitions in the graphene, but the intraband transitions can still induce losses. As such, $\text{Re} (\sigma^{(1)})$ will not entirely vanish, as has also been verified experimentally [34], [35]. Regarding graphene’s nonlinear conductivity, to our knowledge only experimental data for $|\bar{\mu}| \leq 0.26$ eV are available. For example, Gu and co-workers [27] experimentally quantified the nonlinearity of a graphene sample with $|\bar{\mu}| = 0.26$ eV for narrow-band FWM in the near-infrared telecom domain, and they obtained a Kerr nonlinear index $n_2 = 10^{-13} m^2/\text{W}$ and a two-photon absorption coefficient $\beta = 3000 \times 10^{-11} m/\text{W}$. Following the approach in [36] and taking into account that at $|\bar{\mu}| = 0.26$ eV the linear conductivity $\sigma^{(1)} \approx \sigma_0$ yields a complex refractive index, we find that the corresponding non-linear susceptibility is given by $\chi^{(3)}(-\omega_p, \omega_p, \omega_p) = (3.39 + i 3.46) \times 10^{-15} m^2/V^2$. This yields a nonlinear conductivity of $\sigma^{(3)}(-\omega_p, \omega_p, \omega_p) = (1.84 - i 1.80) \sigma_0 \times 10^{-16} m^2/V^2$.

Although experimental data are available only at relatively small chemical potentials, the qualitative trends of the curve in Fig. 3 show that at $|\bar{\mu}| = 0.46$ eV the self-phase modulation nonlinearity is expected to be as large as at $|\bar{\mu}| = 0.26$ eV, allowing us to adopt the $\sigma^{(1)}$-value of Gu and co-workers [27], while the single-photon loss in Fig. 2 is much lower than at $|\bar{\mu}| = 0.26$ eV ($\text{Re} (\sigma^{(1)}) = 0.155 \sigma_0$). Hence, tuning both gates 1 and 2 to a bias voltage at which the underlying graphene sheet acquires $|\mu_{PPM}| = 0.46$ eV is an appropriate working point for the targeted PPM conversion. A detailed overview of the graphene conductivities is provided in Table I. This table also specifies the contributions of the graphene layer to the effective parameters for the graphene-covered SOI converter with PPM operation (see formulas in Appendix).

We now choose an appropriate cross-sectional SOI waveguide geometry with which we can fulfill the PPM condition $\Delta k_{total} \approx 0$. We do not want our choice to depend on the pump power, since we target efficient conversion at different
TABLE I

<table>
<thead>
<tr>
<th></th>
<th>PPM – gate 1</th>
<th>PPM – gate 2</th>
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<tbody>
<tr>
<td>Re(σ(1)(ωp))/σ0 (–)</td>
<td>0.155</td>
<td>0.155</td>
</tr>
<tr>
<td>Re(σ(2)(ωp))/σ0 (–)</td>
<td>0.155</td>
<td>0.155</td>
</tr>
<tr>
<td>n Goldberg (cm²/Vs)</td>
<td>1.84 - i 1.80</td>
<td>1.84 - i 1.80</td>
</tr>
<tr>
<td>(×10⁻¹⁶ m²/V²)</td>
<td></td>
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</tr>
<tr>
<td>αp,g (x10⁴ m⁻¹)</td>
<td>1.27</td>
<td>1.27</td>
</tr>
<tr>
<td>αs,g (x10⁴ m⁻¹)</td>
<td>1.27</td>
<td>1.27</td>
</tr>
<tr>
<td>γCL,g (x10² m⁻¹·W⁻¹)</td>
<td>8.90 + i 9.09</td>
<td>8.90 + i 9.09</td>
</tr>
<tr>
<td>γCL2,g (x10² m⁻¹·W⁻¹)</td>
<td>17.80 + i 18.18</td>
<td>17.80 + i 18.18</td>
</tr>
<tr>
<td>γM1,g (x10² m⁻¹·W⁻¹)</td>
<td>17.80 + i 18.18</td>
<td>17.80 + i 18.18</td>
</tr>
<tr>
<td>γM2,g (x10² m⁻¹·W⁻¹)</td>
<td>8.90</td>
<td>8.90</td>
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For the mode simulations we used the commercial mode solver Lumerical. The graphene layer, patterned to create two separate sheets on top of the two spiral halves, is covered by solid polymer PEO electrolyte [33] to enable gating. For reasons that will be explained in the next section, we assume the waveguide spiral is constructed with an average radius of 23 µm, which for an Archimedes spiral outline as shown in Fig. 1 yields a total propagation distance of 350 µm and a device footprint as small as 2200 µm². For a 220 nm-thick SOI waveguide with an average bending radius of 23 µm, numerical mode simulations with the graphene cover layer and PEO cladding included show that a waveguide width of 670 nm yields a close-to-zero β2 or dispersion parameter D for the TE mode at λp = 1625 nm, as shown in Fig. 4. The chosen cross-sectional waveguide geometry yields a cross-sectional area A’ = 1.5 × 10⁻¹³ m², an effective free-carrier lifetime τeff around 0.5 ns [11], and a linear SOI propagation loss αeff(µ₀/µ)/µs = 34.5 m⁻¹ (the latter corresponds to a power loss of 3 dB/cm). For the free-carrier absorption efficiency and index change efficiency of the SOI waveguide we use σFCA = 1.45 × 10⁻²¹ m² and σFCl = −5.3 × 10⁻²⁷ m³.

Regarding the graphene-to-SOI diffusion rate we can derive from earlier reported experiments [24] that in the case of weakly doped graphene, the graphene-covered converter in the absence of linear absorption (solid grey line); the bare SOI waveguide converter (dashed black line); the bare SOI waveguide converter in case PPM and QPM operation are combined (dotted grey line). For all simulations the signal input power P, in is taken to be 250 µW.

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SOI waveguide converter considered earlier [11], a −20 dB conversion efficiency was achieved at a pump input power of only 110 mW, but the propagation length was more than 40 times longer and the footprint more than 4 times larger than for the graphene-covered foundry-compatible SOI waveguide converter considered here. The solid grey curve in Fig. 5 shows that, when totally neglecting the linear absorption loss of the graphene on top as is done in some studies (see, e.g., [46]), considerably higher performances exceeding −20 dB are predicted. However, even at our working point below the threshold for single-photon absorption induced by interband transitions, the graphene will still cause non-negligible loss associated with intraband transitions, as discussed earlier on and verified experimentally. The solid black curve in Fig. 5 properly accounts for the influence of this loss.

As shown in Fig. 6, our simulation results for the graphene-covered converter indicate a large PPM bandwidth. The −3dB-bandwidth is found to be 43 THz, which is not as large as the 52 THz bandwidth obtained for the extensively dispersion-engineered SOI waveguide considered earlier [11] but still represents a very significant value for a foundry-compatible waveguide with limited dispersion engineering possibilities. The difference between the two values is less than 20%. Hence, although graphene exhibits, like silicon, a strong material dispersion as shown by the imaginary part of the linear conductivity in Fig. 2, the graphene-covered SOI waveguide converter allows for broadband PPM operation.

### B. QPM conversion

For signal and idler wavelengths situated outside the PPM bandwidth, QPM conversion can be employed instead. As a case study, we consider QPM conversion between $\lambda_s = 2370$ nm (i.e. a signal photon energy of 0.523 eV) and $\lambda_i = 1236.4$ nm (i.e. an idler photon energy of 1.003 eV), while pumping at $\lambda_p = 1625$ nm. For the converter of Fig. 1 to operate in the QPM regime, gates 1 and 2 should induce different chemical potentials in the underlying graphene sections so that these acquire FWM nonlinearities of opposite sign. Like in the previous section, the linear absorption loss $\text{Re}(\sigma^{(1)})$ should be kept low. As shown in Fig. 7, the chemical potentials where this requirement is met at all three involved photon energies will vary with the chemical potential as shown in Fig. 8. The qualitative trends of this curve indicate 0.6 eV to 1 eV. To establish efficient QPM conversion, we thus need to determine two chemical potentials within this range that yield strong FWM nonlinearities of opposite sign. Our earlier presented theory [22], [29] predicts that graphene’s third-order conductivity $\text{Im}(\sigma^{(3)}(-\omega_s, \omega_p, \omega_p))$ for FWM at the considered photon energies will vary with the chemical potential as shown in Fig. 8. The nonlinearity reported by Hendry et al. for their wideband FWM experiment and by Gu et al. [27] for their narrow-band FWM experiment are very similar. Therefore, like we did in

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3 Although these pump powers are substantial, no absorption-induced saturation effects are expected in the graphene cover layer since the power residing in the graphene is less than 0.1% of the total power and will give rise to limited absorption below the single-photon absorption threshold. For much higher pump powers (i.e. when using pulsed excitation), saturation could occur. In that case the linear graphene absorption decreases, but also the nonlinearity is expected to go down [45], and a separate study will be needed to assess the resulting conversion efficiency.

4 For the bare SOI converter we here consider the combination of PPM operation with ‘automatic’ QPM operation based on a spatially varying Kerr nonlinearity along the spiral, but a similar result is obtained in case the PPM operation is combined with QPM based on a spatial variation of the dispersion along the spiral.
In the previous section for narrow-band FWM, we can assume that also for broadband FWM $|\text{Im}(\sigma^{(3)}(-\omega_s, \omega_p, \omega_p))| = 1.80 \sigma_0 \times 10^{-16} m^2/V^2$ for a small chemical potential. Taking into account that the trends in Fig. 8 indicate that the nonlinearities at $|\mu| = 0.6 \text{ eV}$ and $0.77 \text{ eV}$ are at least equally as large in absolute values as those at a small chemical potential, we adopt $|\text{Im}(\sigma^{(3)}(-\omega_s, \omega_p, \omega_p))| = 1.80 \sigma_0 \times 10^{-16} m^2/V^2$ and $-1.80 \sigma_0 \times 10^{-16} m^2/V^2$ at $|\mu| = 0.6 \text{ eV}$ and $0.77 \text{ eV}$, respectively. Tuning the bias voltages of gates 1 and 2 such that the underlying graphene sections acquire $|\mu_{\text{QPM1}}| = 0.77 \text{ eV}$ and $|\mu_{\text{QPM2}}| = 0.6 \text{ eV}$, respectively, thus is an appropriate working point for the targeted QPM conversion. A detailed overview of the corresponding graphene conductivities and of graphene’s contributions to the effective parameters of the converter with QPM operation can be found in Table II.

Turning now to the properties of the SOI spiral waveguide, the earlier mentioned choice of an average bending radius value of $23 \mu m$ relies on the requirements for QPM. In the QPM regime the sections where the sign of $\cos(-\Delta k_{\text{total}} \zeta)$ has changed should correspond to the sections where the FWM nonlinearity has a reversed sign as well. For a converter configuration as in Fig. 1 the sign reversal of the nonlinearity occurs every time the spiral angle varies over $\pi$. Following the same reasoning as in our earlier work [12], [14] and taking into account that the nonlinear phase mismatch is small as compared to the linear part, the condition for having FWM in the QPM regime is given by

$$R_{\text{avg}} = \frac{1}{|\Delta k|}$$

with $R_{\text{avg}}$ representing the average radius of the spiral-shaped waveguide. For the pump, signal and idler wavelengths under consideration, the linear phase mismatch $\Delta k$ in the graphene-covered waveguide is equal to $4.4 \times 10^4$ m$^{-1}$, for which Eq. (6) yields $R_{\text{avg}} = 23 \mu m$.

Using the graphene parameter values specified above, we obtain for the effective parameters defined in Appendix the values outlined in Table II. For the remaining simulation parameters we employ the same settings as previously.

To calculate the attainable conversion efficiencies in the QPM regime for the considered graphene-covered SOI waveguide converter and for its bare counterpart, we solve Eqs. (1)-(4) for signal and idler wavelengths 2370 nm and 1236.4 nm, and for pump input powers $P_{\text{in}}$ ranging between 10 mW and 900 mW, and we plot the corresponding conversion efficiencies in Fig. 9. To quantify the QPM bandwidth of the graphene-covered converter, we also solve Eqs. (1)-(4) for varying $\lambda_s$ and $\lambda_i$ in the vicinity of 2370 nm and 1236.4 nm, respectively. The resulting conversion efficiencies are shown in Fig. 10. To illustrate what happens inside the spiral, Fig. 8. Graphene’s nonlinear conductivity for four-wave mixing with a pump photon energy of 0.763 eV and a signal photon energy of 0.523 eV versus chemical potential, as calculated using our earlier presented theory [22], [29]. In the calculations, room temperature is assumed, and the inter- and intra-band scattering rates are taken to be $33 \text{ meV}$. Only the qualitative trends of this curve should be considered; the quantitative nonlinearity values used in the numerical simulations for the converter differ from the values indicated in this graph (see text).
where QPM is obtained through a Kerr-nonlinearity produced as compared to a waveguide without QPM (see, e.g., waveguides is being used. However, all schemes seem to have depends on which of the existing QPM schemes for SOI

At low pump powers, perfor-

 converter in Fig. 9 by applying for all pump powers a

taken to be

centered around

For all simulation results the signal input power

P

µW.

in power of

P

mW can be

At the same time, the PPM signal bandwidth is less than

its performances close to

where the non-zero phase mismatch, although periodically compensated, inevitably results in varying growth rates for the idler along the spiral (see Fig. 11). The main strength of the QPM concept as compared to PPM operation is that it can be applied to signal wavelengths far outside the PPM bandwidth. In this particular case, the pump-signal frequency difference equals 58 THz which significantly goes beyond the 43 THz bandwidth in the PPM regime (see Section IIIA), and even beyond the 52 THz record PPM bandwidth of the extensively dispersion-engineered SOI waveguide considered earlier [11]. We remark that, when totally neglecting the linear graphene absorption in the graphene-covered converter, QPM performances close to −20 dB are predicted as shown by the solid grey curve in Fig. 9.

The use of graphene as a waveguide cover layer opens up different routes towards wideband FWM conversion in foundry-compatible SOI structures. For the spiral-shaped graphene-covered foundry-compatible spiral-shaped SOI waveguide converter not only allows for broadband PPM conversion but also for QPM conversion over considerable bandwidths centered at signal wavelengths very far away from the pump wavelength.

IV. CONCLUSION AND OUTLOOK

The use of graphene as a waveguide cover layer opens up different routes towards wideband FWM conversion in foundry-compatible SOI structures. For the spiral-shaped graphene-covered foundry-compatible spiral-shaped SOI waveguide studied here with a length of a few hundreds of microns, we found PPM conversion efficiencies that approach −20 dB and that are up to 8 dB higher than those of the bare SOI waveguide. At the same time, the PPM signal bandwidth is less than 20% smaller than the record PPM bandwidth achievable in

![Graph showing signal-to-idler conversion efficiency in the QPM regime versus pump input power for different waveguide converters.](image1)

![Graph showing spatial evolution of the idler power within the spiral converter in the QPM regime for a pump input power of 500 mW and a signal input power of 250 µW.](image2)
extensively dispersion-engineered SOI waveguides that are not foundry-compatible. The latter can also yield -20 dB
conversion efficiencies with pump powers that are up to 10
times lower than those considered here, but in that case
waveguide lengths more than 40 times longer and footprints
more than 4 times larger than those used here are required. We
also found that the new graphene-enabled QPM scheme
where the ‘ideal’ scenario of periodically reversing the nonlinearity
also found that the new graphene-enabled QPM scheme where
more than 4 times larger than those used here are required. We
QM schemes for bare SOI waveguides in the best-case
scenario. QPM conversion efficiencies exceeding -30 dB
have been shown for a 3.4 THz -wide band centered at a signal
wavelength that is even outside the record PPM bandwidth
of SOI waveguides incompatible with foundry fabrication
constraints. The possibility of switching between the PPM
and QPM conversion modes is an additional asset that further
leverages the practical usability of graphene-covered foundry-
compatible SOI waveguide converters.

As pointed out in the paper, the broadband character of
graphene’s nonlinear optical behavior has already been experi-
mentally investigated above the one-photon absorption onset
(i.e. $h\nu > 2|\mu|$ or $|\mu| < h\nu/2$) through, amongst others,
wideband FWM experiments in graphene with $|\mu| \approx 0 \text{ eV}$
[26]. Figs. 3 and 8 plotted for given photon energies show that,
as long as $|\mu| \ll h\nu/2$, graphene’s nonlinear characteristics
are practically constant as a function of chemical potential.
Equivalently, when fixing the chemical potential, graphene’s
nonlinearities only weakly depend on the photon energy as
long as $h\nu \gg 2|\mu|$. As a result, graphene samples with $|\mu| \approx
0 \text{ eV}$ indeed exhibit very broadband nonlinear optical prop-
erties from the microwave domain to the visible region [26],
[47]. In this paper, however, we have considered graphene’s
optical nonlinearities at a working point below the one-photon
absorption threshold. We have found that also below the
one-photon absorption threshold strong nonlinearities can be
obtained over a broad range of photon energies, provided that
the graphene chemical potential is tuned to a properly chosen
value. Taking into account that with electrolyte top
gates the chemical potential can be varied (in absolute value)
in a range around $0.3 \text{ nm}$ for which $d_g$
on top of the waveguide. For the modal field simulations, it is
allow to take $d_g$ in a range around $0.3 \text{ nm}$ for which
the mode simulation results converge. We include only the
imaginary part of the linear graphene conductivity $\sigma^{(1)}(\omega)$
in determining the waveguide mode, converting it to an effective
dielectric tensor affecting the optical response of the thin
layer only in the $x$ and $\zeta$ directions. We neglect any optical
response of the graphene in the $y$ direction. The real part of
the linear graphene conductivity, which describes linear loss,
and the nonlinear effects are included by allowing the mode
amplitudes to be slowly varying, in the usual “coupled mode
equation” approach. Our approach is similar in spirit to that of
Lin et al. [9], but we use a strategy [53] that allows for both
modal and material dispersion. The group velocities, including
modal and material dispersion, of the modes are defined as

$$v_\mu = \frac{dw_\mu(k)}{dk},$$

and thus include both contributions to the full dispersion
relation $\omega(k)$ of mode $\mu$. This slightly modifies the norma-
ization condition of the modes [54]; the strategy has
been used earlier for the description of quantum nonlinear
optical effects [55], and the inclusion of nonlinear effects
mirrors the treatment here. We use the function $s_{SI}(x,y)$
($s_{y}(x,y)$) to indicate the location of the silicon (graphene),
taking $s_{SI}(x,y) = 1$ ($s_{y}(x,y) = 1$) where the silicon (the
thin layer modeling the graphene) is present and $s_{SI}(x,y) = 0$
($s_{y}(x,y) = 0$) where the silicon (the thin layer modeling
the graphene) is not present. We find the following formulas for the effective parameters of the graphene-covered silicon waveguide:
\[
\tilde{\alpha}_p = \alpha_{p,Si} + \alpha_{p,g} = (2v_p d_g I_{p})^{-1} \text{Re}(\sigma^{(1)}(\omega_p)) \int e_p^\ast(x', y') \cdot e_p^I(x', y') s_g(x', y') \, dx' \, dy',
\]

\[
\tilde{\alpha}_s = \alpha_{s,Si} + \alpha_{s,g} = (2v_s d_g I_{s})^{-1} \text{Re}(\sigma^{(1)}(\omega_s)) \int e_s^\ast(x', y') \cdot e_s^I(x', y') s_g(x', y') \, dx' \, dy',
\]

\[
\tilde{\alpha}_i = \alpha_{i,Si} + \alpha_{i,g} = (2v_i d_g I_{i})^{-1} \text{Re}(\sigma^{(1)}(\omega_i)) \int e_i^\ast(x', y') \cdot e_i^I(x', y') s_g(x', y') \, dx' \, dy',
\]

\[
\tilde{\gamma}_S = \gamma_{S, Si} + \gamma_{S, g} = (4v_p^2 I_p^2)^{-1} [3 \epsilon_0 \omega_p \chi_S]^{(3)}_{ijkl} \int \left( e_p^i(x', y') \right)^\ast e_p^k(x', y') (e_p^k(x', y'))^\ast e_p^l(x', y') s_{Si}(x', y') \, dx' \, dy' + (4v_p^2 d_g I_p^2)^{-1} [3 \epsilon_0 \omega_S]^{(3)}_{ijkl} \int \left( e_p^i(x', y') \right)^\ast e_p^k(x', y') (e_p^k(x', y'))^\ast e_p^l(x', y') s_g(x', y') \, dx' \, dy',
\]

\[
\tilde{\gamma}_C = \gamma_{C, Si} + \gamma_{C, g} = (2v_p v_s I_p I_s)^{-1} [3 \epsilon_0 \omega_C]^{(3)}_{ijkl} \int \left( e_s^i(x', y') \right)^\ast e_p^k(x', y') (e_p^k(x', y'))^\ast e_s^l(x', y') s_{Si}(x', y') \, dx' \, dy' + (2v_p v_i d_g I_p I_i)^{-1} [3 \epsilon_0 \omega_C]^{(3)}_{ijkl} \int \left( e_i^i(x', y') \right)^\ast e_p^k(x', y') (e_p^k(x', y'))^\ast e_i^l(x', y') s_g(x', y') \, dx' \, dy',
\]

\[
\tilde{\gamma}_M = \gamma_{M, Si} + \gamma_{M, g} = (4v_p I_p \sqrt{v_p v_s I_p I_s})^{-1} [3 \epsilon_0 \omega_M]^{(3)}_{ijkl} \int \left( e_s^i(x', y') \right)^\ast (e_p^i(x', y'))^\ast e_p^k(x', y') s_{Si}(x', y') \, dx' \, dy' + (4v_p I_p \sqrt{v_p v_i d_g I_p I_i})^{-1} [3 \epsilon_0 \omega_M]^{(3)}_{ijkl} \int \left( e_i^i(x', y') \right)^\ast (e_p^i(x', y'))^\ast e_p^k(x', y') s_g(x', y') \, dx' \, dy',
\]

\[
(7)
\]
Here, the fields $\psi_{\mu}^0(x, y)$ indicate only the $x$ and $\zeta$ components of $\mathbf{e}_{\mu}(x, y)$. Furthermore,

$$I_\mu = \int dx dy \, \epsilon_0 \times$$

$$\left( \frac{v_{\text{phase}, x}(x, y; \omega_\mu)}{v_{\text{group}, x}(x, y; \omega_\mu)} \right)^2 n^2_x(x, y; \omega_\mu) |\psi_{\mu}^0(x, y)|^2$$

$$+ \left( \frac{v_{\text{phase}, y}(x, y; \omega_\mu)}{v_{\text{group}, y}(x, y; \omega_\mu)} \right)^2 n^2_y(x, y; \omega_\mu) |\psi_{\mu}^0(x, y)|^2$$

$$+ \left( \frac{v_{\text{phase}, \zeta}(x, y; \omega_\mu)}{v_{\text{group}, \zeta}(x, y; \omega_\mu)} \right)^2 n^2 \zeta(x, y; \omega_\mu) |\psi_{\mu}^0(x, y)|^2$$

where

$$v_{\text{phase}, x,y,\zeta}(x, y; \omega) = \frac{c}{n_{x,y,\zeta}(x, y; \omega)},$$

and

$$v_{\text{group}, x,y,\zeta}(x, y; \omega) = \frac{v_{\text{phase}, x,y,\zeta}(x, y; \omega)}{1 + \frac{\omega}{\omega_d} \frac{\partial n_{x,y,\zeta}(x, y; \omega)}{\partial \omega}}.$$

are respectively the local material phase and group velocities. For $(x, y)$ at a point in the silicon we have $n_x(x, y; \omega) = n_{x,Si}(x, y; \omega) = \sqrt{\varepsilon_{Si}}$, where $\varepsilon_{Si}$ is the (assumed real) relative dielectric constant of silicon. For $(x, y)$ at a point in the thin layer modeling the graphene we have $n_x(x, y; \omega) = n_{x,G}(x, y; \omega) = \sqrt{\varepsilon_{G}}$, where $\varepsilon_{G}$ is the effective relative dielectric constant of the graphene sheet. For $(x, y)$ at a point in the electrolyte cover layer we have $n_x(x, y; \omega) = n_{x,E}(x, y; \omega) = \sqrt{\varepsilon_{E}}$, where $\varepsilon_{E}$ is the (assumed real) relative dielectric constant of the electrolyte.

Turning now to the expressions for the effective linear loss parameters $\alpha_{p/s/i}$ by comparing the values of $\alpha_{p/s/i}$ with the linear loss values that the commercial Numerical MODE software readily calculates for graphene-covered waveguides. An excellent correspondence was obtained with relative differences of only a few percent.

Turning now to the expressions for the effective nonlinear susceptibilities $\chi^{(3)}$ of silicon used in these formulas are equal. The nonlinear conductivities of graphene are given by

$$\sigma_{S}^{(3)} = \sigma_{S}^{(3),ijkl}(-\omega_p; \omega_p, -\omega_p, \omega_p),$$

$$\sigma_{C1}^{(3)} = \sigma_{C1}^{(3),ijkl}(-\omega_1; \omega_p, -\omega_p, \omega_p),$$

$$\sigma_{C2}^{(3)} = \sigma_{C2}^{(3),ijkl}(-\omega_2; \omega_p, -\omega_p, \omega_p),$$

$$\sigma_{M1}^{(3)} = \sigma_{M1}^{(3),ijkl}(-\omega_1; -\omega_1, \omega_p, \omega_p),$$

$$\sigma_{M2}^{(3)} = \sigma_{M2}^{(3),ijkl}(-\omega_2; -\omega_2, \omega_p, \omega_p).$$

For the numerical simulations in the paper we approximate $\sigma_{C1/C2}^{(3)}$ by $\sigma_{S}^{(3)}$ and $\sigma_{M1}^{(3)}$ by $\sigma_{S}^{(3)}$. This approximation, which is generally used in the literature for silicon, allows for relating all nonlinear conductivities of graphene in Eq. (7) to experimentally determined values. We point out that, although to our knowledge the PEO electrolyte we consider is not known to exhibit particularly strong nonlinear optical effects, there exist other polymer electrolytes with relatively high nonlinear optical coefficients of the order of $\chi^{(3)} = 10^{-10}$ esu. $\omega_d = 1.4 \times 10^{-13} m^2/V^2$. But even when using such a highly nonlinear electrolyte cover layer, its contribution to the waveguide’s effective nonlinear parameters would be more than 30 times smaller than that from the graphene sheet. Therefore, we can disregard the nonlinearity contribution from the electrolyte cover layer in the formulas for the effective nonlinear parameters in Eq. (7). We do take the silicon waveguide into account in these formulas because, even though silicon’s $\chi^{(3)}$ is smaller than $1.4 \times 10^{-13} m^2/V^2$, it contributes significantly more to the effective nonlinear parameters than the electrolyte. This is due to the much higher field strength in the silicon waveguide as compared to that in the electrolyte cover layer. Finally, we remark that all effective coefficients in Eq. (7) depend on the position along the waveguide because of the position dependence of the graphene chemical potential realized with the electrolyte gates on top.

ACKNOWLEDGMENT

This work has been supported by the ERC-FP7/2007-2013 grant 336940, by the FWO-Vlaanderen project G.0002.13.N., by the National Sciences and Engineering Research Council of Canada, by IAP BELSPO (IAP P7-35), VUB-Methusalem, and VUB-OZR.

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IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. , NO. , 2015

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[42] The details of our strategy for the derivation in Appendix will be published in a separate paper.


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