Highly efficient phase-matched second harmonic generation using an asymmetric plasmonic slot waveguide configuration in hybrid polymer-silicon photonics

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Abstract: We theoretically investigate the possible increase of the second harmonic generation (SHG) efficiency in silicon compatible waveguides by considering an asymmetrical plasmonic slot waveguide geometry and a $\chi^{(2)}$ nonlinear polymer infiltrating the slot. The needed phase matching condition is satisfied between the fundamental waveguide mode at the fundamental frequency (FF) and second-order waveguide mode at the second harmonic frequency (SHF) by an appropriate design of the waveguide opto-geometrical parameters. The SHG signal generated in our starting waveguide is three orders of magnitude higher than those previously reported for a FF corresponding to $\lambda = 1550$ nm. Then, the SHG performance was further improved by increasing the asymmetry of the structure where nonlinear coupling coefficients as large as 292 psm$^{-1}W^{-1/2}$ are predicted. The device length is shorter than 20 $\mu$m and the normalized SHG conversion efficiency comes up to more than $1 \times 10^5 W^{-1}cm^{-2}$.

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References and links

1. Introduction

Recent years, efficient optical nonlinear effects induced at nanoscale and within short distances have been the hotspot of research and considerably studied for the sake of their key role in future highly-integrated nanophotonic functionalities, such as electro-optic modulation, all-optical signal processing, generation of ultra-short pulses, and ultrafast switching [1, 2]. To further increase device efficiencies, reduce device power consumptions and footprints, a possible route consists in enhancing the local electromagnetic fields, using nonlinear media with high nonlinear susceptibilities and satisfying the phase matching...
condition (PMC) between the interacting waves [3]. In the same time, the compatibility with silicon photonics and ultrafast response are also strongly expected.

Among the nonlinear processes, second harmonic generation (SHG) is frequently studied for its simple theoretical principle, reasonable easiness for demonstration in experiments, and various interesting applications [3]. In silicon photonics, however, SHG cannot be excited directly in silicon because the second-order susceptibility vanishes in this material owing to crystal centro-symmetry. Exploitation of silicon nitride (Si$_3$N$_4$) has been proposed to circumvent this drawback and induce second-order nonlinear processes in silicon compatible structures [4–7]. For now, three mechanisms have been proposed to do this. Firstly, $\chi^{(2)}$ can be induced in silicon waveguides by using a stressing Si$_3$N$_4$ overlayer. Based on such a waveguide geometry, SHG efficiency of about $5 \times 10^{-8}$ under a ns pump peak power of around 0.7 W was realized for a length of two millimeters [4]. Secondly, SHG was proposed in a Si$_3$N$_4$ ring resonator due to the break of centrosymmetry at the interface between the waveguide and the silica cladding. J. S. Levy et al. observed in a 116 µm ring radius resonator a conversion efficiency of $2.86 \times 10^{-4}$ with a 100 µW of second harmonic frequency (SHF) signal generated for a fundamental frequency (FF) pump power of 315 mW [5]. More recently, R. E. P. de Oliveira et al. reported SHG in a 20 µm radius Si$_3$N$_4$ ring resonator by using the electric-field induced SHG process and calculated a conversion efficiency of around $3.68 \times 10^{-3}$ with a pumping power of 75 mW [6].

In order to further increase the efficiency of SHG and reduce the sizes of devices, plasmonic based nonlinear devices are among the most promising candidates to match this expectation due to the ability to allow strong local-enhanced confinement of light beyond the limits imposed by the laws of diffraction in dielectric media [2, 3, 9]. Another advantage of plasmonic structures is that they can respond on the timescale of a few femtoseconds. Many kinds of nonlinear plasmonic structures have been proposed. For instance, efficient SHG has been presented in plasmonic slot waveguides (PSW) [10–12], long-range plasmonic waveguides [13], hybrid plasmonic waveguides (HPW) [14], metal surfaces with nanoscale roughness [15], individual metallic nanoaperture [16], plasmonic particle chains [17], and plasmonic core-shell nanowires [18]. To date, the most used nonlinear material in these structures to realize SHG is lithium niobate (LiNbO$_3$) [11–14]. However, in spite of the generally used continuous wave (CW) pump power of the FF to around 1 W, the peak powers of the generated SHF are usually limited to $10^{-5}$ W [11–13]. Even if it can go up to $10^{-2}$ W in HPW, the corresponding waveguide length to realize this efficiency is one millimeter [14], which is probably too long and not suitable for applications into future integrated nanophotonic circuits. The rather small reported efficiencies are due to the relatively small nonlinear susceptibility in LiNbO$_3$, the moderately large nonlinear coupling coefficients (NCC) between different frequencies, and the absorption loss of the plasmonic modes. Furthermore, LiNbO$_3$ is not easily compatible with silicon photonics, which represents the best solution for high yield and mass production with low cost [19]. In the same time, nonlinear polymers (NP) which have nonlinear susceptibilities exceeding those of LiNbO$_3$ and can be integrated into silicon photonic structures have drawn more and more attention for nonlinear optics and all-optical high-speed signal processing [20–22]. For example, Wenshan Cai et al. demonstrated experimentally an electrically controlled SHG in plasmonic slot with NP in the slot [10]. More recently, L. Alloatti et al. reported an impressive second-order normalized conversion efficiency up to 2900% W$^{-1}$cm$^{-2}$ based on a silicon-organic hybrid (SOH) waveguide [23].

Hence, structures combining the plasmonic and NP have a great potential for nonlinear nano-optics. In this paper, we propose a second-order nonlinear PSW configuration in hybrid polymer-silicon photonics and choose a NP with high $\chi^{(2)}$ as its core nonlinear material. This waveguide is able to tightly confine fields in the subwavelength nonlinear slot both at FF and SHF [24], which is helpful to efficiently reinforce the nonlinear effects. In addition, it can be realized experimentally with state-of-the-art silicon compatible fabrication techniques [10].
With careful choice of the opto-geometrical parameters, the phase-matched SHG at the FF wavelength corresponding to $\lambda = 1550$ nm induced in the proposed waveguide was analyzed by numerical simulations. Then, we modified the SHG performance by enhancing the asymmetry of the PSW. In new structure the NCC has been dramatically enhanced, making it possible the generation of highly efficient SHG with low pump power ($\leq 10$ mW) and short waveguide length ($\leq 20$ $\mu$m).

This paper is organized as follows. In Section 2 we describe the structure of the proposed waveguide, the nonlinear coupled-wave equations (NCE) to model the SHG process, and the method to fulfill the phase matching condition (PMC). In Section 3, the numerical results of SHG in the proposed PSW are presented. In Section 4, we improve the performance of the PSW by increasing the waveguide asymmetry and give the modified results. Then, we conclude in section 5 and give perspectives to the present work.

2. Waveguide structure and nonlinear modeling approach

2.1 Plasmonic waveguide structure

Figure 1 shows the cross-section of the proposed waveguide geometry, which is similar to the one reported in [12] for a LiNbO$_3$-based structure, and with a $\chi^{(2)}$ polymer infiltrated into a metallic slot. The width and height of the NP region are $w$ and $h$, respectively. The considered polymer is the doped, crosslinked organic polymer with a refractive index of $n = 1.643$ and an electrooptic coefficient of $r_{33} = 170$ pm/V at the wavelength of 1550nm [21, 25]. Based on the conversion equation $\chi^{(2)}_{nm} = \delta_{nm} \delta_{in} \delta_{n}^{*} |\epsilon_{in}| / 2$ [26], the corresponding NP second-order nonlinear susceptibility $|\chi^{(2)}_{nm}| = 619.4$ pm/V can be obtained. Metal is defined here as silver due to its relatively low loss in the calculated wavelength range and with a Drude permittivity dispersion given by $\epsilon_{ag} = \epsilon_{\infty} - f_{p}^{2} / (f(f+i\gamma))$, with $\epsilon_{\infty} = 5$, $f_{p} = 2175$ THz, and $\gamma = 4.35$ THz [27].

In order to couple light into such a plasmonic slot waveguide (PSW) from a standard silicon waveguide, Z. Han et al. proposed experimentally a Si-plasmonic taper-funnel coupler, where a 30% coupling efficiency was reported [28]. More recently, R. Thomas et al. presented theoretically a specially designed coupler with a short taper length to couple light into a PSW, where a maximum coupling efficiency of 72% into a 20 nm slot was predicted [29].

2.2 Nonlinear coupled-wave approach

In order to model the nonlinear targeted process in the considered plasmonic waveguide, the nonlinear coupled mode theory is used here [30–33]. For a specific frequency $\omega$ in a nonlinear...
planar waveguide, we consider the nonlinear polarization \( \vec{\bar{B}}^{NL} \) as a source and the corresponding excited electromagnetic field \( \{ \vec{E}, \vec{H} \} \) which propagates along the + z direction fulfills the Maxwell’s equations:

\[
\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} = io\mu \vec{E} \\
\n\nabla \times \vec{H} = \varepsilon \frac{\partial \vec{E}}{\partial t} + \frac{\partial \vec{\bar{B}}^{NL}}{\partial t} = -io\varepsilon \vec{H} - io\bar{B}^{NL}
\]

and can be expanded in terms of all guided modes at the same frequency:

\[
\vec{E} = \sum_{v} \vec{A}_{v}(z) \vec{E}_{v} = \sum_{v} \vec{A}_{v}(z) \vec{E}_{v}(x, y) \exp(ik_{v}z) \\
\vec{H} = \sum_{v} \vec{A}_{v}(z) \vec{H}_{v} = \sum_{v} \vec{A}_{v}(z) \vec{H}_{v}(x, y) \exp(ik_{v}z)
\]

where \( k_{v} \) is the propagation constant, \( \vec{A}_{v}(z) \) is the slowly varied complex mode amplitude, and \( \{ \vec{E}_{v}(x, y) = \vec{E}_{v,t}(x, y) + \vec{E}_{v,z}(x, y), \vec{H}_{v}(x, y) = \vec{H}_{v,t}(x, y) + \vec{H}_{v,z}(x, y) \} \) are the mode profiles of the \( v \)-th guided mode with the subscripts \( t \) and \( z \) representing the transverse and longitudinal components, respectively. The mode profiles have been normalized as:

\[
\frac{1}{2} \iint \vec{E}_{v}(x, y) \times \vec{H}_{v}(x, y) dx dy = \delta_{v}
\]

For a specific guided mode of \( \{ \vec{E}_{v}, \vec{H}_{v} \} \), it satisfies the Maxwell’s equations without the nonlinear part:

\[
\nabla \times \vec{E}_{v} = -\mu \frac{\partial \vec{H}_{v}}{\partial t} = io\mu \vec{E}_{v} \\
\n\nabla \times \vec{H}_{v} = \varepsilon \frac{\partial \vec{E}_{v}}{\partial t} = -io\varepsilon \vec{H}_{v}
\]

By reversing the sign of \( z \) in Maxwell’s equations, we can construct a new solution to Eq. (4) with the form [30, 32]:

\[
\vec{E}_{v}' = \left[ \vec{E}_{v,t}(x, y) - \vec{E}_{v,z}(x, y) \right] \exp(-ik_{v}z) \\
\vec{H}_{v}' = \left[ -\vec{H}_{v,t}(x, y) + \vec{H}_{v,z}(x, y) \right] \exp(-ik_{v}z)
\]

Then, by using the vector identity \( \nabla \cdot (\vec{a} \times \vec{b}) = \vec{b} \cdot (\nabla \times \vec{a}) - \vec{a} \cdot (\nabla \times \vec{b}) \) and based on Eq. (1) and Eq. (4), we obtain:

\[
\nabla \cdot (\vec{E} \times \vec{H}' - \vec{E}' \times \vec{H}) = -io\bar{B}^{NL} \cdot \vec{E}_{v}'
\]

The next step is substituting Eq. (2) into Eq. (6) and integrating both sides of Eq. (6) over the cross-section of the waveguide. Applying the orthogonal normalization condition of Eq. (3) yields the nonlinear coupled-wave equation (NCE) for guided waves:

\[
\frac{\partial \vec{A}}{\partial z} = \frac{i\omega}{4} \iint \left\{ \bar{\vec{B}}^{NL} \cdot \vec{E}_{v}' \right\} dx dy
\]
For a lossy waveguide case, the propagation constant can be written into its real and imaginary parts as: \( k_x = \beta_x + i \frac{\alpha_x}{2} \). Here \( \beta_x \) and \( \alpha_x \) represent the phase propagation constant and attenuation coefficient, respectively. If we set \( A_x(z) = \tilde{A}_x(z) \exp(-\frac{\alpha_x}{2}z) \) and substitute it into Eq. (7), we obtain the following NCE for lossy waveguides:

\[
\frac{\partial A_x}{\partial z} = -\frac{\alpha_x}{2} A_x + \frac{i\alpha_x}{4} \exp(-i\beta_x z) \int \left\{ \hat{P}_{NL}^{\alpha} : \tilde{E}_x'(x,y) \right\} dxdy
\]

(8)

Based on this NCE, we can analyze different kinds of nonlinear processes. The only difference between them lies in the expression of the nonlinear polarization \( \hat{P}_{NL}^{\alpha} \) term dependence over the electrical field. In the present case under consideration here about the SHG process, the FF \( \omega_1 \) is converted into the SHF \( \omega_2 = 2\omega_1 \), and the nonlinear polarization terms at FF and SHF are \( \hat{P}_{NL}^{\alpha} = \varepsilon_0 \chi^{(2)} : \tilde{E}_x \tilde{E}_x^* \) and \( \hat{P}_{NL}^{\alpha} = \frac{1}{2} \varepsilon_0 \chi^{(2)} : \tilde{E}_x \tilde{E}_x \), respectively. Here \( \chi^{(2)} \) is the nonlinear susceptibility. If we consider a single given guided mode both at FF and SHF, the two nonlinear equations describing the SHG process in the nonlinear waveguide are:

\[
\frac{\partial A_x}{\partial z} = -\frac{\alpha_x}{2} A_x + \frac{i\alpha_x}{4} \kappa_x A_x \exp(i\Delta\beta z)
\]

(9)

\[
\frac{\partial A_x}{\partial z} = -\frac{\alpha_x}{2} A_x + \frac{i\alpha_x}{4} \kappa_x A_x \exp(-i\Delta\beta z)
\]

where \( \Delta\beta = \beta_x - 2\beta_x \) is the phase mismatch and \( \kappa_x \) are the coupling coefficients, which are defined by [33]:

\[
\kappa_x = \varepsilon_0 \int \left\{ \chi^{(2)} : \tilde{E}_x(x,y)\tilde{E}_x'(x,y) : \tilde{E}_x'(x,y) \right\} dxdy
\]

(10)

\[
\kappa_2 = \varepsilon_0 \int \left\{ \chi^{(2)} : \tilde{E}_x(x,y)\tilde{E}_x(x,y) : \tilde{E}_x'(x,y) \right\} dxdy
\]

Note that the longitudinal components of the modes were neglected in the nonlinear coupling coefficients calculation because the transverse components of both the hybrid modes and the nonlinear susceptibility dominate all over other components.

In the end, we give the definition of the normalized conversion efficiency [34] as a factor of merit that we propose here to quantify the efficiency of SHG conversion process as follows:

\[
\eta = \frac{P_2(L_p)}{\left[ P_1(0)^{2/3} L_p(cm)^{1/3} \right]}
\]

(11)

where \( P_1(0) \) is the pump power of the FF, \( L_p \) is the length when SHF reaches its maximum (defined as peak position) and \( P_2(L_p) \) is the corresponding maximum output power, respectively. This allows better assessment of the conversion process since it takes the conversion efficiency \( \eta_p = P_2(L_p) / P_1(0) \) (to be maximized), the pump power of the FF wave (to be minimized), and the needed device length (to be minimized) simultaneously into account. It should be noted that this definition is slightly different from the standard one in a lossless waveguide, where the waveguide length is fixed. As the optimized device length \( L_p \) varies here with the pump power, different losses for the FF and SHF are indeed obtained, meaning a variable normalized conversion efficiency under variations of the pump power.
2.3 Key factors to increase the SHG efficiency

The key factors to increase the SHG efficiency both in terms of higher $\omega_1 \rightarrow \omega_2$ conversion yield and smaller device footprint are reducing propagation attenuation, satisfying the phase matching condition (PMC) to $\Delta \beta = 0$, and achieving large coupling coefficients $\kappa$. In the plasmonic slot waveguide (PSW) under study here, these three factors can be fulfilled or optimized by adjusting the waveguide opto-geometrical parameters.

In order to reduce the propagation attenuation, let us first remind that the metal was chosen as Ag due to its relatively low losses and that to further minimize the PSW propagation losses, a polymer with a relatively low index of 1.643 is considered. The choice of the slot width $w$, however, results from a trade-off between the accepted loss level increasing and the obtained field-induced nonlinear effect enhancement by lowering $w$. Besides, an important feature of $w$ is that it affects the PMC, as shown hereafter. For these two reasons, this parameter needs a careful appropriate design.

With respect to the PMC, the most popular methods include birefringence, quasi-phase-matching (QPM) and mode phase-matching techniques [35]. Birefringence is the dependence of the refractive index on the direction of polarization of the optical radiation. By making use of this, it is possible to achieve the PMC between the interacting frequencies with different polarizations [3]. QPM is one of the most effective techniques for the attainment of phase matching in a material that lacks birefringence and is achieved through periodic modulation of the nonlinear coefficient [36]. In the PSW studied here, however, it is not easy to use these two approaches, first because PSW can only support one polarization - the so-called transverse magnetic (TM) one, which is here quasi-TM only, and the polymer periodical poling in a narrow slot is difficult. Another method for achieving PMC in SHG is to make use of the distinction of modal dispersion properties between different frequencies. In general waveguides can support several modes, and the mode effective refractive indices of higher-order modes are lower. Therefore PMC can achieve if the FF propagates at a lower-order mode than the SHF. This approach is simple because it does not require any additional technological step after the waveguide fabrication. For example, PMC can be satisfied between modes with different orders or different symmetries at the FF and the SHF by optimizing the geometrical parameters of the PSW as it was proposed for LiNbO$_3$-based plasmonic waveguides [11, 12].

We have adopted a similar approach in the present paper, first in the simplest possible configuration before extending it to improve the SHG efficiency as shown hereafter in section 4. Figure 2(a) shows the effective indices of the two guided modes as functions of the slot height $h$ for a free space FF wavelength of 1550 nm and a slot width $w = 50$ nm. The red and blue lines represent the obtained effective indices for modes at the FF ($\lambda_1 = 1550$ nm) and the SHF ($\lambda_2 = 775$ nm), respectively. We can see that the fundamental mode (labeled 0-th mode) at the FF has a crossing with the second-order mode (labeled 1-st mode) at the SHF indicating a point of PMC. For the considered case of a SiO$_2$ substrate, which has indices of 1.444 and 1.454 for FF and SHF [37], respectively, the PMC occurs for the slot height $h = 489$ nm. At this point, the effective indices for the FF and the SHF are $2.2068 + 0.0068i$ and $2.2069 + 0.0063i$, respectively. The corresponding $E_x$ distributions of the different modes are plotted in Figs. 2(b), 2(c) and 2(d). All the mode profiles shown here have been calculated by using the finite-element-based commercial COMSOL software.
3. SHG in the proposed starting plasmonic slot waveguide geometry

Now we calculate the SHG for the case of Fig. 2 where the 0-th mode at the FF is converted into the 1-st mode at the SHF. The corresponding calculated coupling coefficient is \( \kappa_1 = \kappa_2' = 71 \text{ psrm}^{-1} W^{-1/2} \). Figure 3 is a plot of the power of FF and SHF waves as a function of the propagation distance for an input power of FF source of 1 W. It is shown that a peak power of the generated SHF wave up to 0.021 W is revealed at a propagation length of only 17.9 \( \mu \)m. The corresponding normalized conversion efficiency is \( 6.55 \times 10^3 \text{ W}^{-1} \text{cm}^{-2} \). This result is larger than the one obtained in LiNbO\(_3\)-based PSW devices by about three orders of magnitude with same pump power at the FF [12]. The improvement of the SHG performance mainly results from two aspects. On one hand, the considered polymer has a smaller index compared to LiNbO\(_3\). This leads to a larger optical power confined into the nonlinear slot region and to a lower waveguide loss level [24]. On the other hand, the larger \( \chi^{(2)} \) in the considered polymer enlarges the coupling coefficients \( \kappa_{1,2} \).
Fig. 3. Optical powers of the FF and SHF waves versus the propagation distance for a pump power of 1 W in the structure depicted in Fig. 2.

Starting from this basic result, further improvement is investigated hereafter by adjusting the compromise between the in-slot field confinement and the optical propagation losses. To do so, we analyze the influence of the slot width on the SHG process performance. In Fig. 4, the slot height to satisfy the PMC, the nonlinear coupling coefficient ($\kappa$), the peak efficiency ($\eta_p$) and peak position ($L_p$) of the SHG process, and the corresponding normalized conversion efficiency ($\eta$) are plotted versus the slot width for a FF pumping power of 1 W. As can be seen, when the slot width decreases, the height required to ensure the PMC decreases and the coupling coefficient increases correspondingly due to the stronger confinement of the field in a smaller area. As a result, the maximum power of SHF increases and the propagation length to realize this efficiency becomes shorter, as is shown in Fig. 4(b). The normalized efficiency increases as well. It can be concluded that the PSW has better SHG property with smaller width. However, it is necessary to stress also that the fabrication feasibility should be taken into consideration, so that too narrow slots cannot be considered.

Fig. 4. (a) Slot height $h$ to satisfy the PMC needed for the SHG process and associated coupling coefficient $\kappa$ between the two coupled modes, (b) peak efficiency $\eta_p$ and peak position $L_p$, (c) normalized conversion efficiency $\eta$.
4. Improvement of SHG efficiency by tailoring the waveguide mode asymmetry

What limits the interest of the mode phase-matching method to satisfy the PMC is that the spatial overlap integration between modes with different orders or different symmetries is always less than that between modes with same orders or same symmetries. This in turn results to small nonlinear coupling coefficients (NCC), as defined in Eq. (10). For example, we can see in Fig. 2(b), that the 0-th mode field distribution at the FF is nearly symmetrical in the nonlinear area. However, in the same time, it is shown in Fig. 2(d) that the 1-st mode field distribution at the SHF is nearly anti-symmetrical in the domain of integration. This will inevitably lead to relatively small coupling nonlinear coefficients.

In order to overcome this drawback and enlarge the NCC between the two considered modes, we increase the asymmetry of the PSW by using a Si$_3$N$_4$ substrate with larger indices at the FF ($n_{Si3N4} = 1.99$) and SHF ($n_{Si3N4} = 2.1$). The new structure is still compatible with silicon photonics. The PMC is satisfied for $w = 50$ nm and $h = 490$ nm from Fig. 5(a) and the corresponding mode profiles are shown in Fig. 5(b), Fig. 5(c) and Fig. 5(d), respectively. At the PMC point, the geometrical size of the waveguide is almost the same as in Fig. 2. But the mode profiles become quite asymmetrical especially for the 1-st mode at the SHF. In this case, the calculated NCC is up to 292 psm$^{-1}$W$^{1/2}$.

![Fig. 5. Design of the waveguide with Si$_3$N$_4$ sunstrate for satisfying the PMC.](image-url)
that the maximum efficiency is increased up to 20% and that the propagation length (around 12.5µm) to realize this efficiency is shorter as well. The normalized conversion efficiency is calculated to \( \eta = 1.3 \times 10^5 \text{ W}^{-1}\text{cm}^{-2} \), which is over one order of magnitude of further improvement if compared with our starting structure. The principle of this improvement can be seen more clearly in Fig. 7, where plots of the normalized \( E_x \) distributions along the cutline of \( x = 0 \) are shown. For the case of a SiO\(_2\) substrate [Fig. 7(a)], the positive and negative parts of the 1-st mode (blue dotted line) at the SHF have comparable amplitudes, hence making the nonlinear overlap integration with the 0-th mode field small. With respect to the case of Si\(_3\)N\(_4\) substrate [Fig. 7(b)], however, the negative part of the 1-st mode becomes negligible in the integration domain. This indicates that the counteraction effect is lower and in turn contributes to the enhancement of the 0-th/1-st NCC. In addition, it should be noted that as the distribution of the generated SHF becomes less symmetric in the modified structure, the in-and-out light coupling efficiency will be easier from/into standard strip silicon waveguides.

![Fig. 6. Optical powers of the FF and SHF waves versus the propagation distance for a pump power of 1 W in the structure depicted in Fig. 5.](image)

![Fig. 7. Normalized \( E_x \) distribution at \( x = 0 \) for the case of SiO\(_2\) substrate (a); Si\(_3\)N\(_4\) substrate (b). The red solid line and blue dotted line correspond to 0-th mode at the FF and 1-st mode at the SHF, respectively. The domain between the two vertical lines is the nonlinear area to integrate.](image)

In the previous sections, a CW pump power of 1 W was considered to facilitate the direct comparison with the results reported in previous works that considered this pumping condition [12–14]. However, it should be noted that lowering the pumping power is highly desirable and could enable low-power nonlinear all-optical operations amenable to various practical applications in future generations of integrated photonic circuits. Besides, the input power should be chosen carefully so that the intensity in the sub-wavelength slot remains lower than the damage threshold of the material. Since the modified waveguide has so large NCC, we show that the second harmonic can be efficiently generated under low pump power. Figure 8(a) shows the peak position and efficiency as a function of the pump power with all other parameters and conditions being the same as in Fig. 6. As expected, it is shown that the
conversion efficiency is greatly affected by the pump power, while the peak position only moderately varies, while the change of the calculated normalized conversion efficiency is small as well, as it is shown in the left Y-axis of Fig. 8(b). We can see that the plasmonic waveguide length remains shorter than 20 µm in all cases, while the normalized conversion efficiency can exceed $1 \times 10^5$ W$^{-1}$ cm$^{-2}$. Moreover, it should be emphasized that within this nonlinear PSW, the SHG efficiency still remains around 0.4% even if the input power of the FF is as low as to 10 dBm, which represents a continuous wave optical power easily available. This efficiency is over the one in a Si$_3$N$_4$ ring resonator where a pump power of 75 mW was used [6]. Moreover, the optical power of the generated SHF is then still around 40 µW, as shown in the right Y-axis of Fig. 8(b), i.e. is comparable to values reported in previous work that considered a 1 W pumping power [12]. This dramatic improvement makes the proposed plasmonic waveguide geometry very promising and competitive for low-power all-optical signal processing.

![Fig. 8. Peak position $L_p$, peak efficiency $\eta_p$, normalized conversion efficiency $\eta$ and maximum output power $P_2(L_p)$ of SHF versus the input pumping power of FF.](image)

5. Conclusion

In conclusion, we have proposed a silicon compatible nonlinear plasmonic slot waveguide (PSW) with a nonlinear polymer infiltrated the metallic slot. For the SHG induced in this PSW, the phase matching condition between the fundamental frequency (FF) and second harmonic frequency (SHF) can be satisfied with appropriate designs of the opto-geometrical parameters. Efficient SHG, about three orders of magnitude above the one reported in recent works obtained for LiNbO$_3$-based structures, was demonstrated and the influence of the slot width on SHG efficiency was numerically analyzed. Then, the SHG performance was further improved by one order of magnitude by increasing the asymmetry of the proposed waveguide. In the modified proposed geometry, a normalized SHG conversion efficiency above $1 \times 10^5$ W$^{-1}$ cm$^{-2}$ is predicted for a propagation distance shorter than 20 µm. The output power of the SHF generated in the optimized structure for a low pumping power (PP) of 10 mW is comparable to the one obtained in previous works for a 1 W PP. This obtained dramatic improvement of the nonlinear efficiency allows envisaging practical applications using low-power nonlinear SHG-based all-optical signal processing.

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