The 25th Iranian Conference on
Optics and Photonics (ICOP 2019),
and the 11th Iranian Conference on
Photonics Engineering and
Technology (ICPET 2019).
University of Shiraz,
Shiraz, Iran,
Jan. 29-31, 2019

تولید هارمونی دوم تطبیق فاز شده مبتنی بر پاشندگی مد در موجبر سیلیکنی شیاردار غیرمتقارن با پوشش پلیمر غیرخطی

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چکیده- در این مقاله یک موجبر سیلیکنی شیار دار غیرمتقارن با پوشش پلیمر غیرخطی برای تولید کارآمد هارمونی دوم از باند فروسرخ میانی ($\lambda = 3.1$ µm) به باند فروسرخ نزدیک ($\lambda = 1.55$ µm) پیشنهاد می‌شود. شرط ضروری تطبیق فاز بین مد اصلی از فرکانس اصلی و مد سوم از فرکانس هارمونی دوم تولید شده با طراحی دقیق ابعاد موجبر تحقق می‌یابد. بازده ٪ ۲۴/۷ با در نظر گرفتن توان ورودی فقط ۱۰ mW پیش بینی می‌شود که با مقادیر گزارش شده قبلی قابل مقایسه است. مفهوم ارایه شده را می توان به سایر آثار غیرخطی مرتبه دوم مانند جمع و تفاضل دو فرکانس بسط داد.

کلید واژه- تطبیق فاز، تولید هارمونی دوم، موجبر شیار سیلیکنی

Modal Phase-Matched Second Harmonic Generation in Asymmetric Silicon Slot Waveguide Coated with a Nonlinear Polymer

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Abstract- In this paper, an asymmetric silicon slot waveguide coated with a nonlinear polymer is proposed to obtain efficient second harmonic generation (SHG) from mid-infrared ($\lambda = 3.1$ µm) to near-infrared ($\lambda = 1.55$ µm) wavelengths. The required phase matching is fulfilled between fundamental mode at fundamental frequency and third-order mode at SHG by carefully designing the waveguide dimensions. A conversion efficiency of 24.7% is predicted for a low pump power of 10 mW which is comparable to the previously reported results. Our concept can be extended to other second-order nonlinear processes like sum and difference frequency generation.

Keywords: Second harmonic generation, Silicon slot waveguide, Phase matching

1. Introduction

Silicon slot waveguide (SSW), composing of a low-index nanoscale slot layer sandwiched between two silicon ridge waveguide, has been the subject of many investigations for different applications due to its high confinement of the optical field in the slot region. In particular, usage of SSW for sensing application demonstrate up to 5-fold performance enhancement as compared to standard waveguide structures [1]. Also, SSW paves the way to realize high-performance electro-optic modulator by covering and filling the slot region of SSW with an electro-optic organic polymer. Polymer-coating SSW (PCSSW) electro-optic modulator with an impressive bandwidth of greater than 100 GHz, the ultralow power consumption of 0.7 fJ/bit are reported in the literature[2, 3].

Besides, PCSSW can be employed to achieve high efficient second-order nonlinear processes like second harmonic generation (SHG), sum and difference frequency generation (SFG, DFG) and parametric amplification. The main requirement for such nonlinear processes is phase matching which should be satisfied [4]. For example, in SHG, phase matching implies that the effective indices of PCSSW at the fundamental frequency (FF) and SHG frequency should be identical i.e. $n_{2\omega} = n_{\omega}$. Due to the normal dispersion of materials as well as optical confinement of waveguide, this situation is difficult to achieve and hence special technique is needed to fulfill the phase matching condition [4]. In the literature, two approaches for PCSSW have been suggested. One is using of quasi-phase matching (QPM) by periodically poling the nonlinear polymer inside the specially doped PCSSW [5]. However, it's practical implementation has an additional fabrication complexity. Another possibility for achieving phase matching is to exploit modal dispersion properties. In modal dispersion, higher-order (instead of fundamental) mode is excited for SHG wavelength while the fundamental mode is excited at the fundamental frequency (FF). This method benefits from the fact that the effective refractive index of waveguide decreases as the mode order increases. For single slot SSW, the modal dispersion-based phase matching cannot be obtained [6]. To resolve this problem, double slot SSW is proposed to enable modal dispersion phase matching [6]. However, it is desirable to obtain the modal dispersion phase matching in single PCSSW.

Here, we show that the modal phase matching can be fulfilled in single PCSSW by shifting its slot to one side forming an asymmetric PCSSW. The phase matching condition is satisfied between fundamental mode at FF and 3th-order mode at SHG. An SHG efficiency of 24.7% is obtained which is comparable to the previously reported results.

2. Theory and design

Fig. 1(a) depicts the perspective view of the proposed device. It is composed of asymmetric PCSSW which is similar to that of a symmetric PCSSW except with the slot offset to one side. The waveguide dimension of W_{Si} = 820 nm and h = 340 nm are reserved and the slot width and offset are denoted by w and s, respectively. Nonlinear polymer has a high $\chi^{(2)}$ only inside the slot. This can be achieved by poling the polymer at its glass transition temperature and by applying voltage [7]. To apply the necessary electric field, SSW and slab layer are doped with phosphorus to a concentration of 2×10^{16} cm^{-3} to aid the electrical operation of the device. We consider a nonlinear polymer with a refractive index of 1.68 and 1.58 at λ = 1.55 and 3.1 μm, respectively, taking into account its material dispersion [6]. Also, the refractive indices of Si and SiO_2 and their wavelength dispersion properties are taken from [8].

To explore phase matching in the structure, the slot width w is fixed at 70 nm. Using an FDTD solver, the effective refractive indices of the fundamental mode at FF and first three modes at SHG of PCSSW as a function of the slot shift s is plotted in Fig. 2. Representative profile modes of the major component, E_x, are illustrated in Fig. 1(b)-(e). To attain phase matching condition, the effective refractive indices of the waveguide at FF and SHG

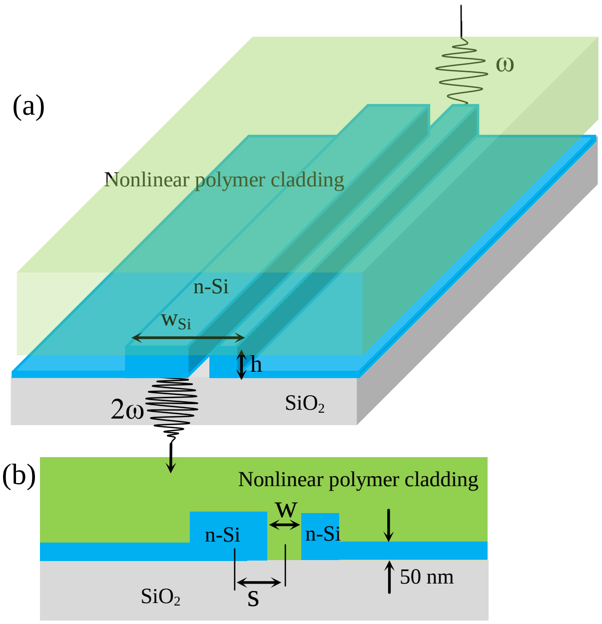

Fig. 1(a): The perspective view of proposed devices for SHG. (b) the cross section of asymmetric silicon slot waveguide.

should be identical. According to the results, the fundamental mode at FF has a crossing with the 3th-mode at SHG indicating a point of phase matching. The phase matching point occurs at slot shift of s = 235 nm where the refractive index of both FF and SH modes is equal to 2.000.

Apart from satisfying phase matching condition, high nonlinear coupling coefficient, κ, which is determined by mode overlap between modes at FF and SHG as well as $\chi^{(2)}$ value is essential for obtaining efficient SHG. The κ can be defined as [5, 9]

$$\kappa = \varepsilon_0 \iint \chi^{(2)} : \vec{E}_{SH}\, \vec{E}^*_{FF} \,.\, \vec{E}^*_{FF}\, dxdy \tag{1}$$

in which ε_0 is vacuum permittivity, E is the normalized electric mode profile. Our calculations show the κ in the proposed structure is 7.58 ps/m/W$^{1/2}$. Next, the value of slot width w is varied and the slot shift is adjusted to fulfill the phase matching conditions. The results are shown in Fig. 3. One can see that with wider slot width, the required slot shift decreases. Also, the largest reachable nonlinear coupling coefficient is κ =7.58 ps/m/W$^{1/2}$, and it can be obtained with the waveguide dimensions of w = 70 nm and s = 235 nm.

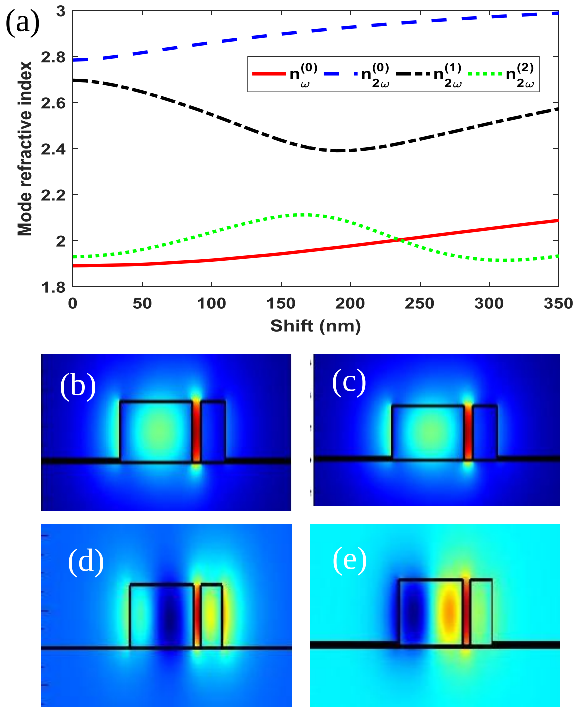

Fig. 2 (a): The effective refractive indices of fundamental mode at FF and first three modes at SHG of PCSSW as function of slot shift s for fixed slot width of w = 70 nm. (b), (c), (d) and (e) represent E_x profile of fundamental mode at FF ant first three modes at SHG, respectively.

3. SHG efficiency

The performance of SHG can be investigated by numerically solving well-known coupled mode equation [5, 9]

$$\frac{dA_1}{dz} = -\frac{\alpha_1}{2}A_1 + i\,\frac{\omega}{4}\kappa A_2(z)A_1^*(z)\exp(i\,\Delta z) \tag{2.a}$$

$$\frac{dA_2}{dz} = -\frac{\alpha_2}{2}A_2 + i\,\frac{\omega}{4}\kappa^* A_1^2(z)\exp(-i\,\Delta z) \tag{2.b}$$

where j =1 refers to the FF and j = 2 refers to the SH. A_i represents the complex slowly varying mode amplitude, α_i is the absorption coefficient, $\Delta = \beta_2 - 2\beta_1$ is the phase mismatch in which β_i is the propagation constant. Note that, α and β are related to the effective refractive index of the waveguide through the relations $\alpha = (4\pi/\lambda)\,\mathrm{Im}(n_{eff})$ and $\beta = (2\pi/\lambda)\,\mathrm{Re}(n_{eff})$.

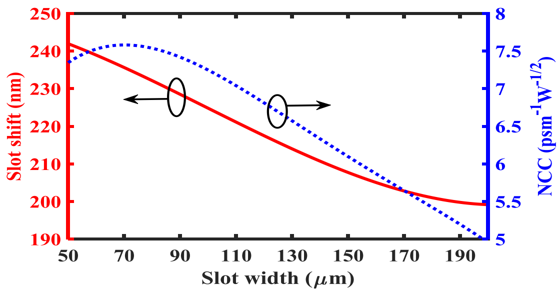

Fig. 3: The required slot shift value to satisfy phase matching condition for different slot width and the corresponding nonlinear coupling coefficient (NCC) for fixed overall waveguide dimension of W_{Si} = 820 nm and h = 340 nm.

The evolution of FF and SH envelope powers i.e. $|A_{FF}|^2$ and $|A_{SH}|^2$ as a function of propagation distance for w = 70 nm and s = 235 nm are drawn in Fig. 4. We assume the input pump power of P_{FF} = 10 mW and α_{FF} = 4.2 dB/cm (the doped Si and scattering loss contribute 2.2 and 2 dB/cm to the total loss[10, 11], respectively) and α_{SH} = 2.6 dB/cm (the doped Si and scattering loss contribute 0.6 and 2 dB/cm to the total loss[10, 11], respectively). The FF power drops quickly due to loss and conversion process while SH power increases first with L, and after reaching its maximum value at the $L \simeq 11$ mm where the conversion efficiency is 24.7%, it starts to decrease. This is because initially, the FF power is strong enough to generate SH power that overcomes waveguide loss and the power of SH wave accumulated. Meanwhile, attenuation of FF power causes that locally generated SH power cannot compensate the optical loss and therefore the SH power starts to decrease. Our results are comparable to other reported SHG in integrated platforms [5, 12, 13]

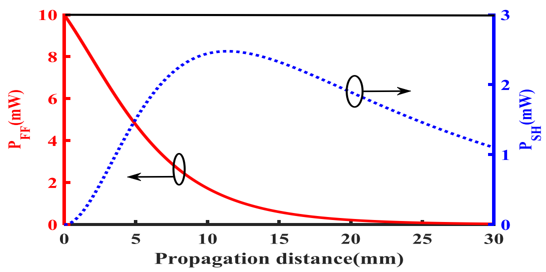

Fig. 4: The evolution of FF and SH powers along propagation distance. The inset shows the influence of FF power on SHG power and optimum propagation distance.

4. Conclusion

In conclusion, we have designed an asymmetric SSW coated with a nonlinear polymer for SHG. The phase matching condition for SHG in the proposed structure is achieved between fundamental mode at FF and 3th- mode at SHG by engineering the waveguide dimensions. Our simulations show the SHG efficiency of 24.7% with only 10 mW pump power at length of 11 mm. Our concept can be extended to other $\chi^{(2)}$-based nonlinear processes like sum and difference frequency generation.

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