Second-harmonic generation in a metal-clad nonlinear optical waveguide

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Abstract: Efficient optical nonlinear effects in waveguides play an important role in integrated photonic functionalities. The dispersion characteristics need to be well designed to satisfy the phase-matching condition of the interacting waves in waveguides. Here we demonstrate a novel phase-matching process of second-harmonic generation (SHG) in a symmetrical metal-cladding optical waveguide (SMCOW) with a nonlinear guiding layer. Ultrahigh order modes in SMCOWs possess small propagation constants, and can be actively tuned to satisfy the phase-matching condition via free-space coupling. We establish a model of SHG in the SMCOW and experimentally verify it as well. This mechanism could also be applied to or referenced in other nonlinear frequency conversion processes.

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References and links

1. Introduction

Optical waveguide devices, with their capability of confining light in small volumes, can effectively enhance the efficiency of nonlinear processes [1–5]. Many researches about frequency conversion in waveguides have been reported [6–8]. The phase-matching condition in waveguides requires that the propagation constants of the interacting waves satisfy momentum conservation. In most cases, the device requires precise dispersion engineering, thus causing difficulties in fabrication. Over the past decade, symmetrical metal-cladding optical waveguides (SMCOWs), sustainable of ultrahigh-order guided modes, have been intensively investigated [9–14]. Ultrahigh-order guided modes in SMCOWs possess many fascinating characteristics, such as small propagation constants, strong negative dispersion, and large Goos–Hänchen shift. SMCOWs have been proposed and demonstrated for various applications, such as slow light devices [10,11], superprism spectrometers [12] and precise displacement detection [13,14]. Nonlinear effects in SMCOWs, however, have not been studied yet. Here, we explore a novel way of frequency conversion in such an SMCOW whose guiding layer is replaced by a nonlinear medium. Efficient second-harmonic generation (SHG) is achieved by taking the advantage of the small effective refractive index of ultrahigh-order guided modes to facilitate the phase matching of the fundamental wave (FW) and second harmonic (SH). The propagation constant of FW is tuned and brought to match the phase-matching condition, rather than designing and managing the dispersion characteristics of the SMCOW itself. Thus, phase matching can be achieved at wavelengths in a wide range. Moreover, the ultrahigh-order guided modes also ensure that both FW and SH resonate at the phase-matching condition. The light beam is transferred into the SMCOW from a top metal surface from free space directly [11]. The device is, therefore, compact. For a high quality factor (Q factor) sample, most of the energy can be coupling into the waveguide, and the signal of SH can be directly observed.

In this paper, we experimentally demonstrate the observation of an efficient SHG in a nonlinear SMCOW. A single crystalline lithium niobate (LN) slab is used as the guiding layer. The difference between the small propagation constants of FW and SH is tuned to the phase-matching condition to encourage the SHG process. The power of SH is dramatically enhanced by the cavity at the phase-matching point. A theoretical analysis is also explored which agrees with experimental results well.

2. Theoretical model

Thick SMCOWs possess lots of fascinating optical properties over conventional all-dielectric optical waveguides. One unique feature of SMCOW is the existing of ultrahigh-order guided modes. The order of guided modes in a sub-mm SMCOW can be much higher than 1,000. Thus, the polarization depended phase shift in total internal reflection at the dielectric/metal interface can be negligible [9]. For an optical waveguide consisting of a thick guiding layer and two metal-cladding layers, the reduced dispersion equation for ultrahigh-order modes can be written as:

\[ k_0 n^2 - N^2 = m \pi, \tag{1} \]
where \( k_0 = \frac{2\pi}{\lambda} \) is the propagation constant in vacuum. \( h \) and \( n \) are the thickness and the refractive index of the guiding layer, respectively. For an isotropic medium, the dispersion of SMCOWs is polarization degenerated for the incident light. While, for an anisotropic guiding layer, SMCOWs becomes polarization dependent due to birefringence of the guiding substrate. \( N = \frac{\beta}{k_0} \) is the effective refractive index, where \( \beta \) is the propagation constant of guided modes, and \( m \) is the mode order. The mode order \( m \) is a very large integer for ultrahigh-order guided modes. One characteristics of SMCOWs is that the effective refractive index can be much smaller than that in the guided wave layer (which can be even smaller than that in air), since light confinement in the guiding layer is not realized by total internal reflection but pure mirror reflection. For ultrahigh-order guided modes, it is only meaningful to explore their characteristics when the effective index is small for their desirable small propagation constants and extreme sensitiveness to the refractive index change.

In our experiment, we designed an SMCOW with a ‘sandwich’ structure, as shown in Fig. 1. A 0.5 mm thick of LN crystal was used as the guiding layer, and a thin silver film (~30 nm) of upper layer is used to couple the pump light into the waveguide. A thick silver film (~200 nm) of back layer is used for to confine light in the guiding layer. An additional thickening upper layer is introduced in the middle section the SMCOW to reduce out-coupling during light propagation. The length of the middle segment is 7 mm, which is also the wave propagation length. The optical axis of LN is along the Z direction, which means the SMCOW in our experiment is polarization sensitive to the input. In this sample, the mode order is typically of the order of magnitude of \( 10^7 \), thus the phase shift during reflection at the interfaces is negligible. The exact order of the excited mode can be calculated according to Eq. (1).

![Fig. 1. (a) Schematic of SHG in an SMCOW. (b) Schematic of light rays and the formation of optical modes in waveguides. (c) SHG requires that the propagation constants of interacting modes are phase matched.](image)

As in Fig. 1, Beam 1 is coupled into the SMCOW by free-space coupling, and a portion of Beam 1 is reflected, denoted as Beam 2. Beam 3 is the light emitted from the waveguide after propagating through the middle segment, which contains FW and SH. For the SHG, we have

\[
\beta_{\text{SH}} = 2\beta_{\text{FW}},
\]

\[
\beta_i = k_i \sin(\theta),
\]

where \( \beta_i \) (i denotes SH or FW) is the propagation constant of SH and FW in the waveguide, \( k_i \) is the propagation constants in vacuum, and \( \theta \) is the incident angle. Figure 2(b)
schematically shows the light rays representation and the formation of different order guiding modes in waveguides. The electric field amplitude becomes almost zero near the core–cladding interface. Therefore the FW and SH are standing waves along the transverse direction (the X direction). The FW in the guiding layer generates SH at the propagation direction, which satisfies the Eq. (2). The propagation constants of the interacting guided waves are required to be phase matched, as depicted in Fig. 1(c). When the propagation constant of SH satisfies Eq. (1), the SH could excite a mode in the SMCOV and be enhanced dramatically. Because of resonance in the X direction, the transverse components ($\kappa$) of FW and SH along the X direction are not required to be equal to each other. According to Eqs. (2) and (3), one can find that the exit angles of FW and SH are the same when the phase-matching condition is satisfied. Otherwise, the FW and SH are two separate spots in the far field, and the SH is generated by the mode excited by the scattering of the FW guided mode. This theory of nonlinearity has been suggested for SHG in waveguides [15].

3. Experiment and discussion

The experimental setup is depicted in Fig. 2(a). Nanosecond pulses (1064 nm, 10 ns, 200 Hz) generated from a solid state Q-switched laser are used. A beam of TM polarization is incident on the SMCOV sample after passing through a small hole in the screen. The SMCOV sample is held in a vertical position. The pump has a diameter of approximate 1 mm. The angle of incidence of the pump light is adjusted using a precise rotation stage (accuracy ± 0.01°) to select the mode to be excited. Most of FW is reflected by the SMCOV when the mode is not activated. When the incident angle satisfies the mode coupling condition, the extraordinary reflection of FW emerges as a concentric-ring pattern projected on the screen, as schematically shown in Fig. 2(a) [16], and a large portion of the pump light is coupled into the SMCOV.

![Fig. 2. (a) Experimental setup for the observation of SHG in SMCOV. (b) The intensity dependence of generated SH coupled out versus incident angle.](image)

When the incident angle is adjusted to the phase-matching angle, the signal of SH in Beam 3 becomes bright dramatically. The polarization of output second-harmonic signal is measured to be TE polarized by use of a Glan prism, which means the nonlinear process is Type I oo-e phase-matching scheme. The intensity of the generated SH in the vicinity of the phase-matching point is measured with the input power of 10 mW, as shown in Fig. 2(b). The angle full-width at half maximum (FWHM) bandwidth of the intensity is about 0.08°. The angle of the peak is at 30.13° (equal to the incident angle), where the modes of FW and SH satisfy the phase-matching condition. The conversion efficiency is measured to be about 1% (ratio of the SH and incident FW power). Considering the propagation loss of about 0.05 dB/mm of the sample, the conversion efficiency is relatively high. The efficiency can, in principle, be improved by use of higher pump intensity. However, due to the thin metal cladding in the coupling segment of the SMCOV, the capability of our device is limited in handling intensive nanosecond pulses. The damage threshold is estimated to be 20 mW in
our experimental condition, equivalent to 250 kW/cm². This can be improved by coating of dielectric layers to form wide bandgap Bragg mirrors on both sides to replace the metal cladding. Due to the scattering of the guiding layer, the adjacent modes can also be stimulated by the directly excited waveguide mode [16]. When we change the incident angle to excite an arbitrary mode order of FW, a weak signal of SH can always be observed at the exit angles. This angle does not change as the incident angle changes. This phenomenon also proves that the SH generation can be only enhanced during the phase-matching condition. Thus, in the experiment, two or more points of SH can be occasionally observed at the same time at some specific angles.

The signal power of SH generation can be calculated by solving the coupled wave equations [17]. Considering the enhancement effect of the SMCOW on the pumping light energy, one also needs to take the field overlap of the two modes into account. The energy of the outgoing second harmonic is given by the following equation [15]:

\[
P_{\text{SH}} = \frac{C_{\text{SH}}(\theta) C_{\text{P}}^2(\theta) \left( \omega_p \chi^{(2)} L P_p \right)^2}{8 n_p^2 n_{\text{SH}} c E_0 A_p} A_{\text{SH}} \sin \left( \frac{\Delta k L}{2} \right) f(A_p, A_{\text{SH}}),
\]

\[
C_i(\theta) = \frac{P_{\text{WG}}}{P_{\text{in}}} = \frac{P_{\text{out}}(\theta)}{P_{\text{in}}(\theta)},
\]

where \(P_{\text{SH}}\) and \(P_p\) represent the power of the generated SH and the pump power in the waveguide, respectively. \(C_i(\theta)\) is coupling factors of the FW and SH. \(\omega_p\) is the angular frequency of the pump and \(\varepsilon_0\) is the permittivity of vacuum. \(\chi^{(2)}\) is the effective second-order coefficient. \(A_p\) is the mode area, \(L\) is the propagation length, \(n_i\) is refractive index, \(c\) is the speed of light in vacuum, and \(\Delta k = \beta_{\text{SH}} - 2 \beta_{\text{FW}}\) is the phase mismatch. \(C_i(\theta)\) takes into account the resonant power in the SMCOW (divide the power inside the waveguide \(P_{\text{WG}}\) by the input power \(P_{\text{in}}\)) [18], where \(P_{\text{in}}(\theta)\) and \(P_{\text{out}}(\theta)\) represent the input power and output power which can be directly measured in the attenuated total reflection (ATR) experiment. When the incident angle satisfies phase-matching condition, \(\Delta k = 0\) and \(C_i(\theta)\) reaches its peak value. Thus, the strongest signal of SH is observed. Sequentially increasing or decreasing the incident angle will decrease \(C_i(\theta)\) rapidly, which results in a low conversion efficiency.

From Eq. (4), one finds that the angle bandwidth of SH depends on the coupling factors of the FW and SH. When the phase-matching condition is satisfied, as the propagation length grows, the power of SH increases. The signal of SH generation1 is enhanced intensively when the pump and SH are both resonant at 30.13°. In this sample, the intensity of SH in Beam 3 was about 10 times larger than that of Beam 2 with an input power of 10 mW. The experimental data is in good agreement with the theoretical prediction, as in Fig. 2(b). Thus, it can be reaffirmed that the formation of SH is the result of phase-matching condition between the ultrahigh-order modes of FW and SH.

4. Simulation and analysis

The ATR spectrum of the SMCOW sample is measured using a similar setup as shown in Fig. 2(a). Collimated light beams from two continuous diode lasers of 1064 nm and 532 nm are used. Angular scans are carried out by use of a computer controlled \(\theta - 2\theta\) goniometer [19]. The reflected light is detected with a photodiode by averaging the intensity of Beam 2. In the experiment, the ATR spectrum is measured in the range of 25° and 35°.
Results of the ATR spectra during the free-space coupling are shown in Fig. 3. A series of dips in reflectivity due to resonant transfer of energy into guided modes can be clearly observed. From the analysis of reflectivity, more than 50% of the light energy has been coupled into the optical waveguide. Due to the birefringence of LN, the SMCOW in our experiment is polarization dependent. The experimental data of TM polarization of 1064 nm and the calculated ATR spectra are shown in Fig. 3(a). The experimental result agrees well with the theoretical prediction, except for a small deviation of the incident angle and the coupling efficiency. The ATR spectrum of the TE polarized light at wavelength of 532 nm is measured under the same condition as shown in Fig. 3(b). Three phase-matching conditions are met at the incident angles of 26.95°, 30.13°and 33.09°, as marked by the dashed lines in Fig. 3. As one can see, the ultrahigh-order modes of FW and SH make them easier to resonate together. In the experiment, enhanced SH was also obtained at the angles of 26.46°, 30.13° and 33.36°. We obtain the brightest signal of SH at 30.13°, because the dips of FW and SH are closest to each other.

Fig. 3. (a) The experimental and simulation ATR spectra of the SMCOW sample at the wavelength of FW ($E_0 = -58.488 + 1.172i$ at 1064 nm). (b) The experimental ATR spectrum of the SMCOW at the wavelength of 532 nm.

From the results, one can see that the mechanism of frequency conversion is similar in SMCOWs and traditional waveguides. It’s also worth mentioning that if we change the wavelength of pump, we can also generate SH by just adjusting the incident angle. For an integrated optical device where precise dispersion management must be well considered before fabrication, the stringent phase-matching condition always results in poor performance. Ultrahigh-order modes in SMCOWs, on the other hand, provide an alternative way to achieve phase matching by actively tuning the propagation constants to match the phase-matching condition, which overcomes this problem in traditional waveguides. By the way, as LN is a photoelectric material, the dispersion characteristics can also be precisely controllable by applying voltage on the metal layers.

5. Conclusions

In summary, SHG in a metal-clad nonlinear optical waveguide is explored. The principle of frequency doubling in the SMCOW is analyzed. This new method for SHG in waveguides possesses some unique advantages. One of the biggest advantages is that the tunability of the small effective refractive index in the SMCOW can make the satisfaction of the phase-matching condition easier, which can be used to overcome the poor regulation of traditional waveguides. Additionally, the ATR spectra are measured and calculated to confirm the
theory of SHG in the SMCOW. We believe nonlinear effects in SMCOWs would be of practical importance in applications of highly-integrated photonic functionalities.

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