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Proposal for sum-frequency generation based on modal phase-matching in photonic crystal fibers

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ABSTRACT

In this paper, we report on a feasible phase matching between three low-order modes guided in an appropriately designed photonic crystal fiber (PCF). The phase matching condition for sum-frequency generation (SFG) can be realized over a large wavelength range by modifying the air holes size and the lattice pitch. This can be achieved in the proposed photonic crystal fiber because the sum-frequency wave propagating in a LP_{02} mode leaks more into the low refractive index cladding than does the fundamental wave. By "feeling the cladding", the LP_{02} mode compensates for the increased refractive index of the silica at the sum-frequency wavelength. The numerical results show that the SFG in the proposed nonlinear PCF can be tunable, and the pump and sum-frequency waves are well-confined in the fiber core region.

1. Introduction

Optical frequency conversion by second-order nonlinear interaction is an efficient way to extend the spectral range of laser sources and all-optical wavelength multiplexing. For instance, the sum-frequency generation (SFG), which is associated mainly with nonlinear crystals with high second-order susceptibilities such as KTP [1] and PPLN [2], is widely used for obtaining visible laser light. Compared to these nonlinear crystals, silica fibers have several excellent properties such as long interaction length, low cost, high transparency and the high optical damage threshold. Strictly speaking, second-order nonlinear effects are forbidden in silica fibers because silica is centrosymmetric materials. However, by using thermal poling techniques, the centrosymmetry can be broken and a large permanent second-order nonlinearity can be created in silica fibers [3,4]. Thus, poled silica fibers are an attractive all-optical solution to frequency conversion.

Second-order nonlinear effects in poled silica fiber include several different parametric processes, for example, sum-frequency generation, difference-frequency generation, second-harmonic generation, etc. To our knowledge, the present research generally focused on how to generate second-harmonic wave in silica fiber [5–12]. However, it is surprising that the studies of SFG in fiber are limited to two experiments, one was done in 1980 [13], and the other was done in 1981 [14]. In both of them, the two-wave sum frequency light was generated from the pump and the Raman Stokes lines. But the conversion efficiency was so low (~0.1%) that it is hard to be used in practical applications.

For efficient SFG from two frequencies ω_1 and ω_2, the waves need to be phase-matched: $\Delta\beta = \beta_{SF} - \beta_{\omega 1} - \beta_{\omega 2} = 0$, in which $\beta_{\omega 1}$ and $\beta_{\omega 2}$ are the modal propagation constants of the two pump waves and β_{SF} is the modal propagation constant of the sum-frequency wave. Ideally, we would like to use the fundamental modes of three waves, simply because their Gaussian modal field distributions are easily compatible with other laser sources. Nevertheless, the phase matching condition of these three fundamental modes is hard to be realized in optical fibers as both material and waveguide chromatic effective index dispersions are decreasing functions of the wavelength (in the normal dispersion region). In order to overcome this difficulty, in this paper, we propose a feasible modal phase matching between three low-order modes guided in an appropriately designed nonlinear SFG PCF. It is worthy to note that modal phase matching has been used for second-harmonic generation (SHG) [15]. The main difference between SFG and SHG in PCF is that two pump wavelengths are equal in the second-harmonic generation process while two pump wavelengths are unequal in the sum-frequency generation process. Nevertheless, the phase matching conditions for SHG and SFG can be realized by modifying the air holes size and the lattice pitch.

The principle of modal phase matching is to design a waveguide where the phase matching condition between the fundamental waves and their sum-frequency wave is fulfilled when they propagate in different modes. However, the use of higher-order modes has well-known drawbacks: the first one is non-gaussian intensity profile for the sum-frequency wave which is not easily exploitable while the second one leads a low modal overlap. Fortunately, the

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first disadvantage can be overcome by using a mode converter [16], and the other limitation can be overcome by choosing the appropriate modes [17]. Thus, mode phase matching is worth considering. In addition, we note that the pump waves propagate in the LP_{01} mode and the sum-frequency wave propagates in the LP_{02}-mode, the required second-order nonlinear coefficient (1 pm/V) can be created by using a “simple” poling technique [18], which can avoid the length limitation. The phase matching condition between three low-order modes can be fulfilled by tuning fiber structure.

2. Geometric structure

The proposed PCF structure used in our simulation is depicted in Fig. 1. It consists of a silica core region surrounded by three rings of air holes in a triangular lattice, which forms the cladding. The structure parameters are characterized by air hole pitch Λ and air hole diameter d respectively. In order to compute the field distribution and its modal effective indices, a full-vector finite element method (FEM) with anisotropic perfectly matched layers is applied [19]. The refractive index of the air holes is set to 1 in the computation, and the background refractive index is obtained from the Sellmeier equation for fused silica.

3. Nonlinear SFG PCF design

First of all, let us focus on the C-band, two pump wavelengths are chosen at = 1.54 μm and λ_{P2} = 1.55 μm respectively, then the corresponding sum-frequency wavelength is at λ_{SF} = 0.7725 μm. Fig. 2 shows the phase-matching of the two pump waves and the sum-frequency wave in an appropriately designed PCF with Λ = 3 μm. We can learn that the modal propagation constants of the pump and sum-frequency waves decrease with d increasing, and when d = 2.337 μm, $\beta_{\omega 1} + \beta_{\omega 2} = \beta_{SF}$ = 11.5392 μm^{-1}, which means that the phase matching condition for SFG is fulfilled. Phase matching works here because the sum-frequency wave is in a higher-order mode and so leaks more into the low refractive index cladding than its fundamental wave does. In this situation, the LP_{02} mode is sufficient to compensate for the increased refractive index of the silica at the sum-frequency wavelength.

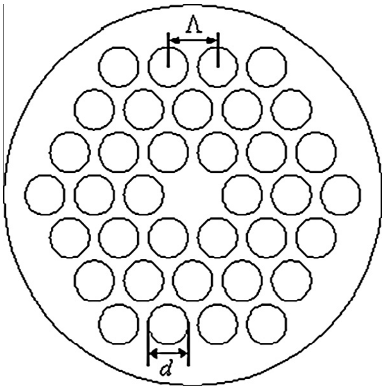

Fig. 1. Cross-sectional view of the proposed MF.

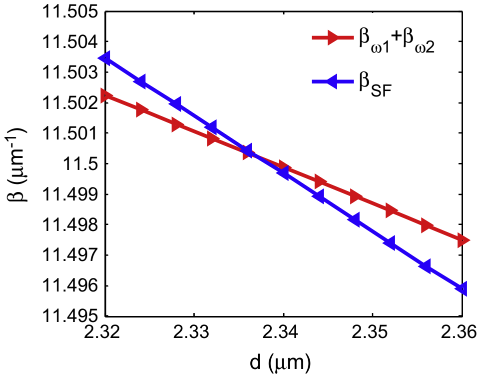

Fig. 2. Phase-matching of the LP_{01} mode of the two pump waves at λ_{P1} = 1.54 μm, λ_{P2} = 1.55 μm and the LP_{02} mode of the sum-frequency wave at λ_{SF} = 0.7725 μm for the case with Λ = 3 μm.

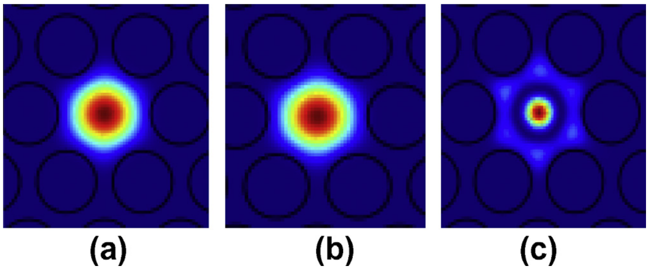

Fig. 3. The mode field patterns of the LP_{01} mode at λ_{P1} = 1.54 μm (a) , λ_{P2} = 1.55 μm (b) and the LP_{02} mode at λ_{SF} = 0.7725 μm (c) for the case with d = 2.337 μm and Λ = 3 μm.

The intensity distributions of the LP_{01} mode at λ_{P1} = 1.54 μm, λ_{P2} = 1.55 μm and the LP_{02} mode at λ_{SF} = 0.7725 μm are shown in Fig. 3. It can be seen that these three modes are well-confined in the core. However, Compared to the two LP_{01} modes, the field distribution of the LP_{02} mode is less confined in the core. This is because the sum-frequency wave is in a higher mode and so leaks more into the low refractive index cladding than the fundamental wave does. The effective area (A_{ovl}) which takes account of the overlap between the LP_{01} and LP_{02} modes can be calculated by the following equation [9].

$$A_{ovl} = \left| \iint E_{SF}^{*} E_{P1} E_{P2}\, dx\, dy \right|^{-2} \tag{1}$$

where E_{SF}^{*}, E_{P1} and E_{P2} are normalized sum-frequency and pump modes. The calculation results show that the effective area is as large as 13.108 μm^2 when λ_{P1} = 1.54 μm, λ_{P2} = 1.55 μm and λ_{SF} = 0.7725 μm. From this calculation result and the intensity distributions of these three modes, we can learn that the LP_{02} mode has a large nonlinear overlap with the fundamental LP_{01}mode. But unfortunately, a large effective area means weak nonlinearity because the conversion efficiency is inversely proportional to the effective area.

In Table 1, we show that phase matching condition for SFG can be still fulfilled in a single photonic crystal fiber when one of pump wavelength is changed. Such as if we change λ_{P1} from 1.54 μm to 1.35 μm or 1.38 μm, then their corresponding sum-frequency wavelength is changed from 0.7725 μm to 0.77123 μm or 0.77198 μm, which means that the SFG in our proposed nonlinear PCF can be tunable. Another interesting finding is that the modal

Table 1
Phase matching for SFG between two pump waves at different wavelengths and effective area for the case with d = 2.337 μm and Λ = 3 μm. L = 10 cm, $\tilde{\chi}^{(2)}_{xxx} = 1$ pm/V.

λ_{P1} (μm)	λ_{P2} (μm)	λ_{SF} (μm)	$\beta_{\omega 1} + \beta_{\omega 2} = \beta_{SF}$ (μm^{-1})	A_{ovl} (μm^2)
1.535	1.55	0.77123	11.5591	13.102
1.538	1.55	0.77198	11.5474	13.106
1.54	1.55	0.7725	11.5392	13.108
1.54	1.553	0.77324	11.5277	13.111
1.54	1.5555	0.77385	11.5182	13.114