Mid-infrared fiber optical parametric oscillator using a three-hole suspended-core chalcogenide fiber

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Abstract. A three-hole As$_2$S$_5$ suspended-core fiber with a zero-dispersion wavelength of 2 μm is proposed to construct a mid-infrared (MIR) fiber optical parametric oscillator (FOPO). The numerical model of the MIR FOPO is established and a tuning range from 2 to 5 μm for the idler light is predicted.

1. Introduction
Mid-infrared (MIR) lasers are of great interest due to their various applications in spectroscopy, medicine, and military. However, the output wavelength range of a conventional MIR laser is limited and it is hard to find a material to cover a wide wavelength region in the MIR band. Contrastingly, fiber optical parametric oscillator (FOPO) using a pump to generate a pair of signal and idler through four-wave mixing in a cavity has been proved to be a promising way to generate broadband MIR lasing. For MIR FOPO, chalcogenide fibers are a kind of promising nonlinear materials due to its low intrinsic loss and high nonlinearity in MIR band [1].

The generation of the pair of signal and idler is controlled by the phase-matching condition. Only when the signal and idler wavelengths together with the pump wavelength satisfy the phase-matching condition, the signal and idler can be efficiently created. In order to meet the phase-matching condition, the pump wavelength should be located near the zero-dispersion wavelength (ZDW) of the used fiber. However, the ZDW of bulk chalcogenide glass is around 5 μm or even longer and it is a key problem to shift the ZDW to 2 μm or even shorter. The suspended core structure is a feasible way to realize wide band ZDW shift [2]. Recently, thulium-doped fiber lasers (TDFLs) provide high-quality lasing from 1.8 to 2.1 μm with high average power and high slope efficiency [3], which becomes a promising choice to serve as the pump of a chalcogenide FOPO. In this paper, we proposed a MIR FOPO using a three-hole As$_2$S$_5$ suspended-core fiber (SCF) with a core diameter of 2.6 μm as the gain medium. A tuning range of 2-5 μm can be achieved by tuning the TDFL from 1.9 to 2 μm.

2. Simulation Model
Figure 1(a) shows the dispersion curve for the bulk chalcogenide glass and the SCF whose cross-section structure is shown in the inset of Figure 1(a). The dispersion curve is calculated using the material refractive index of As$_2$S$_5$ in [4]. Tuning the core diameter while the width of the bridge is fixed as 0.6 μm, one can find that the ZDW of the SCF will moves to shorter wavelength as the core diameter reduces. When the core diameter is set to 2.6 μm, a ZDW equal to 2 μm can be obtained. Such a SCF is suitable for a MIR FOPO pumped by a TDFL. Considering a degenerate four-wave
mixing (DFWM) into the effective phase-matching equation, one can get the signal and idler wavelengths those satisfy the effective phase-matching condition when the pump power is 1 W, as shown in Figure 1(b). The idler wavelength can vary from 2 to 5 μm if a TDFL with a tuning range of 1.9-2 μm is used as the pump.

Figure 1. (a) Dispersion performance and the designed SCF structure; (b) Phase-matched signal and idler wavelength as a function of the pump wavelength when pump power is 1 W.

The FOPO structure used for analysis is illustrated in Figure 2, a single resonant cavity is designed, which ensure the signal light resonant in the cavity and keep other lights pass the gain medium only once. The resonant cavity consists of four mirrors: M1, M2, M3 and M4. All of these mirrors are of high reflectivity at the signal wavelength. M1 is antireflective at the pump wavelength and M2 is antireflective at the idler wavelength. Using the coupled-wave equations for DFWM [5] and taking two-photon absorption (TPA) effect into consideration, the nonlinear parameter is expressed as

\[
\gamma_j = \frac{n_2 c \alpha_j}{2 A_{eff}} + i \beta_{TPAj} \quad (j = p, s, i)
\]

(1)

where \(n_2\) is the nonlinear refractive index coefficient, \(c\) is the speed of light, \(\gamma_{p,s,i}, \alpha_{p,s,i}, \beta_{TPA_{p,s,i}}, A_{eff_{p,s,i}}\) is the nonlinear parameter, the angular frequency, the TPA coefficient and the effective mode area for the pump, signal, and idler lights, respectively. \(A_{eff}\) is the effective mode area defined as:

\[
A_{eff} = \frac{\int |F(x, y)|^2 \, dx \, dy}{\int |F(x, y)|^2 \, dx \, dy}
\]

(2)

where \(F(x, y)\) is the normalized mode distribution.

Assuming that the pump is provided by a nanosecond pulse laser, it can be considered as a quasi-CW pump and the time derivative in the coupled-wave equation can be ignored. The cavity length can
be tuned by moving the two mirrors M3 and M4 to ensure the synchronization between the pump and the reflected signal light. Therefore, the phase of the signal at the beginning of each round trip is reasonable to be set as 0. For such a FOPO configuration, the boundary conditions for the amplitude of each interacted wave is expressed as

\[ A_i(z = 0, t) = \sqrt{1 - \alpha_{\text{linear}}} \cdot A_i(z = L, t) \]

\[ A_p(z = 0, t) = \sqrt{P_p} \]

Here, \( A_{p,i} \) is the amplitude of the pump and signal light, \( P_p \) is the input pump peak power, \( \alpha_{\text{linear}} \) is the additional cavity loss excluding the fiber loss at the signal wavelength (i.e., introduced by the mirrors and the fiber coupling), and \( L \) is the length of SCF. With these boundary conditions, the coupled-wave equations can be solved using iterative algorithms. The generated signal and idler powers can be numerically obtained.

3. Results and discussion

Using the above-mentioned theoretical model, the DFWM coupled-wave equations are solved using a home-built fourth-order Adams-Bashforth method. Assuming the pump wavelength is 1.95 \( \mu \)m, and the phase-matched signal and idler wavelengths are calculated to be 1.318 and 3.749 \( \mu \)m, respectively. Taking this case as an example, the performance of the MIR FOPO is analyzed. The numerical parameters used in the simulation are as follows: \( n_2 = 0.54 \times 10^{-17} \), \( A_{\text{effs}} = 4.308 \mu \text{m}^2 \), \( A_{\text{effp}} = 4.646 \mu \text{m}^2 \), \( A_{\text{effi}} = 6.113 \mu \text{m}^2 \), \( \beta_{\text{TPAs}} = 0.102 \text{ cm/GW} \), \( \beta_{\text{TPAp}} = 0.0072 \text{ cm/GW} \), \( \beta_{\text{TPAi}} = 0.00005 \text{ cm/GW} \), \( \alpha_p = \alpha_s = \alpha_i = 1 \text{ dB/m} \), \( \alpha_{\text{linear}} = 50\% \), and \( \Delta \beta = -2\gamma_p P_p \).

![Fig. 3. (a) Output idler power as a function of number of signal round trip for \( P_p = 1 \) W and \( L = 0.2 \) m; (b) Threshold pump power as a function of fiber length.](image)

Fig. 3. (a) Output idler power as a function of number of signal round trip for \( P_p = 1 \) W and \( L = 0.2 \) m; (b) Threshold pump power as a function of fiber length.

To verify the stability of the model, the number of cycles for oscillation is simulated, as shown in Figure 3(a). It is shown that the signal eventually reaches stable oscillation with the MIR output of 0.131 W for \( P_p = 1 \) W and \( L = 0.2 \) m. Figure 3(b) shows the pump threshold of the FOPO as a function of the fiber length. Increasing the fiber length from 0.02 to 0.3 m, the threshold pump power rapidly decreases from 7.4 to 0.5 W. It means that the requirement to the pump power will be reduced if a longer SCF is used.

In conclusion, a MIR FOPO is suggested utilizing a three-hole As\(_2\)S\(_3\) SCF with a core diameter of 2.6 \( \mu \)m and pumping by a nanosecond TDFL with output wavelength around 1.95 \( \mu \)m. The idler wavelength can cover the wavelength band of 2-5 \( \mu \)m if the pump wavelength is tuned from 1.8 to 2 \( \mu \)m and the pump threshold can be as low as 0.5 W.

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