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Design and optimization of tellurite hybrid microstructured optical fiber with high nonlinearity and low flattened chromatic dispersion for optical parametric amplification

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ABSTRACT

The linear phase-mismatch and the optical signal gain in the highly nonlinear tellurite hybrid microstructured optical fiber based on the degenerate four-wave mixing are numerically simulated. The core and the cladding of this fiber are designed by TeO_2–Li_2O–WO_3–MoO_3–Nb_2O_5 and TeO_2–ZnO–Na_2CO_3–P_2O_5 glass, respectively. This fiber has high nonlinearity and at the same time the chromatic dispersion is flattened and close to zero. High optical signal gain and broad band can be obtained by using a short length of this fiber with low pump power.

1. Introduction

Four-wave mixing (FWM) process occurring in optical waveguides is a third order nonlinear optical phenomenon [1–5]. It can be used in many applications: optical demultiplexers, wavelength converters, optical parametric amplification (OPA), correlated photons pairs generation in quantum cryptography, generation of laser rays in telecommunication, and supercontinuum (SC) generation in biomedical applications [6–11]. The broad band FWM relies on broad band nonlinear phase-matching (PM), which requires careful control of the group-velocity dispersion of the fiber. The precise PM is easy to achieve in the vicinity of the zero-dispersion wavelength or anomalous chromatic dispersion regime, which is very important for highly efficient FWM occurrence in the optical fiber [12,13]. OPA in optical fiber is one of FWM applications, which has already been widely researched [14,15]. In order to obtain higher and broader optical signal gain, high pump power and the fiber with high nonlinearity and long length are usually needed. However, long fiber length tends to induce the nonlinear phase-mismatch due to chromatic dispersion fluctuation along the fiber, and high pump power will lead to other nonlinear effects, such as stimulated Brillouin scattering and stimulated Raman scattering, making FWM effect difficult to distinguish.

Tellurite glass fiber have raised attention due to their wide transparency in the infrared region and nonlinear refraction index close to 2 or 3 orders of magnitude larger than that of a conventional single-mode fiber [16–18]. In addition, tellurite microstructured optical fibers (MOFs) have aroused a lot of interest because of their controllable dispersion and high nonlinearity [19–21]. Their application in optical parametric oscillator has already been numerically simulated [22]. Tellurite MOFs are especially advantageous for OPA. This is because highly efficient and broad band wavelength conversion of FWM requires high nonlinearity and short fiber length so as to reduce the nonlinear phase-mismatch. Another soft-glass chalcogenide MOFs have already been used for OPA [8,23–24].

In this paper, a tellurite hybrid MOF (HMOF) with high nonlinearity and low flattened chromatic dispersion is designed and optimized for OPA based on the degenerate FWM. The core and the cladding of the tellurtie HMOF are designed by TeO_2–Li_2O–WO_3–MoO_3–Nb_2O_5 (TLWMN) and TeO_2–ZnO–Na_2CO_3–P_2O_5 (TZNP) glass, respectively. The chromatic dispersion of this fiber is flattened and close to zero. The linear phase-mismatch, the optical signal gain and the bandwidth are numerically simulated by using a short length of this fiber with low pump power.

2. Basic theoretics

FWM is a third-order nonlinear parametric process governed by PM condition. In this work we are mainly interested in the

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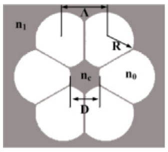
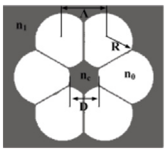
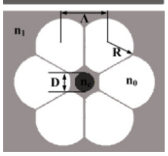
Table 1
Structures and parameters of three kinds of MOF.

MOF	Schematic of the structure	D [μm]	R [μm]	Λ [μm]	n_1	n_0	n_c	n_2 [$m^2 W^{-1}$]	γ [$W^{-1} km^{-1}$]
1#		1.734	1.13	1.997	1.45	1	1.45	2.6×10^{-20}	44.73
2#		1.734	1.13	1.997	2.005	1	2.005	5.9×10^{-19}	101.53
3#		0.894	1.13	1.997	1.568	1	2.058	2.45×10^{-18}	6642

process denoted as degenerate FWM which involves the single pump wave frequency $\omega_1=\omega_2=\omega_P$. The degenerate FWM theory has been well described and can be expressed by the following equations [25, 26]

$$\frac{\partial A_p}{\partial z}=i\gamma[(|A_p|^2+2(|A_i|^2+|A_s|^2))A_p +2A_iA_sA_p^*e^{i\Delta\beta z}]-\frac{\alpha_p}{2}A_p \quad (1)$$

$$\frac{\partial A_{i(s)}}{\partial z}=i\gamma[(|A_{i(s)}|^2+2(|A_p|^2+|A_{i(s)}|^2))A_{i(s)} +A_p^2A_{i(s)}^*e^{i\Delta\beta z}]-\frac{\alpha_{i(s)}}{2}A_{i(s)} \quad (2)$$

where A_p, A_i and A_s are the field amplitudes of the pump, the idler and the signal waves, respectively, and $\gamma=n_2\omega/A_{eff}\bullet c$ is the nonlinear coefficient, n_2 is the nonlinear refraction index and A_{eff} is the effective mode area. α is the loss coefficient, and $\Delta\beta$ is the linear phase-mismatch. Due to the difference of A_{eff} at the idler, signal and pump waves, γ is also different. In the paper the approximate average value of γ at the pump wave is used.

In degenerate FWM, the pump wave is annihilated, and simultaneously the idler and signal waves are created. The conservation of energy and nonlinear PM must satisfy the following equations

$$2\omega_p=\omega_i+\omega_s \quad (3)$$

$$\kappa=\Delta\beta+2\gamma P=0 \quad (4)$$

where ω_p, ω_i and ω_s are the angular frequencies of the pump, idler and signal waves, respectively. P is the launched peak power. $\Delta\beta$ is the linear phase-mismatch and can be expressed by

$$\Delta\beta=\beta_i+\beta_s-2\beta_p=\frac{n(\omega_i)\omega_i}{c}+\frac{n(\omega_s)\omega_s}{c}-\frac{2n(\omega_p)\omega_p}{c} \quad (5)$$

where $n(\omega_i)$, $n(\omega_s)$ and $n(\omega_p)$ are the refraction indices at ω_i, ω_s and ω_p, respectively. If we know $n(\omega_i)$, $n(\omega_s)$ and $n(\omega_p)$, the linear phase-mismatch can be calculated based on Eq. (5) and it will include all the high-order dispersions (β_2, β_4, β_6, β_8…). As some papers reported, if we consider up to fifth-order dispersion, the more commonly used equation is (6) which is based on Taylor expansion where β_2 and β_4 are evaluated at ω_p and $\Delta\omega=|\omega_s-\omega_p|$ [1,27–29].

$$\Delta\beta=\beta_2(\Delta\omega)^2+\frac{1}{12}\beta_4(\Delta\omega)^4 \quad (6)$$

If the nonlinear response is assumed to only consist of an instantaneous Kerr-part, and the mode profile of the guided mode is constant, the optical signal gain (G_s) is given by

$$G_s=\frac{P_s(L)}{P_s(0)}=1+\left(\frac{\gamma P}{g}\right)^2\sinh^2(gL) \quad (7)$$

where L is the fiber length, $P_s(L)$ and $P_s(0)$ are the signal power at different length. $g=\sqrt{(\gamma P)^2-\left(\frac{\kappa}{2}\right)^2}$ is parametric gain which is usually considered real. It implies that $(\gamma P)^2-\left(\frac{\kappa}{2}\right)^2>0$ and can also be formulated as $-4\gamma P<\Delta\beta<0$ [1]. Maximum signal gain occurs when $\Delta\beta=-2\gamma P$, and $g_{max}=2\gamma P$.

When $\Delta\beta\le-4\gamma P$, $g=i\sqrt{\left(\frac{\kappa}{2}\right)^2-(\gamma P)^2}$. And Eq. (7) can be written into

$$G_s=\frac{P_s(L)}{P_s(0)}=1+\left(\frac{\gamma P}{g_i}\right)^2\sin^2(g_iL) \quad (8)$$

3. Structures of three kinds of MOFs

In order to illuminate the advantage of the tellurite HMOF for the broad band FWM, three kinds of MOFs were numerically simulated. Table 1 shows the structures of the silica MOF (1#), the tellurite MOF (2#) and the tellurite HMOF (3#). These three MOFs are designed by silica glass, TeO_2–ZnO–Li_2O–Bi_2O_3 (TZLB) glass, and the TLWMN and TZNP glasses, respectively. For 3# MOF, the background is made by TZNP glass and the core by TLWMN glass. Glass composition is very important for 3# MOF fabrication because during the fiber drawing process, the core and the background should be thermally stable and compatible, and thermal expansion and softening temperature of two tellurite glass must be similar. TLWMN and TZNP glasses have similar thermal and mechanical properties and the same fiber drawing temperature (370 °C), which is necessary for successful preparation of 3# MOF. The transmission spectrum of the TLWMN glass was from 0.33 μm to 5.91 μm, which was measured by an ultraviolet visible near infrared (UV–VIS–NIR) spectrophotometer (~0.30–2.50 μm) and a Fourier transform infrared spectrophotometer (~2.50–25 μm).