Design Tailored Efficient Broad-Band Fiber Optic Light Source for Mid-IR Molecular Spectroscopy

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Abstract: An efficient compact ~ 80 cm long microstructured optical fiber-based broad-band (5.0-6.3 µm) mid-IR light source with power conversion efficiency > 40% has been designed by exploiting FWM with commercially available CO laser as pump.

OCIS codes: (060.4370) Nonlinear Optics, Fiber; (190.4380) Nonlinear Optics, Four wave mixing; (060.4005) Microstructured fibers; (160.4330) Nonlinear optical materials.

1. Introduction

Rapid advancement in fiber fabrication techniques and development of suitable relatively low-loss materials of good transparency in recent years have opened up a new platform for mid-IR photonics in the wavelength range 2 - 25 µm [1,2]. Within this mid-IR window, 5 – 6.5 µm is very essential for molecular spectroscopy of various organic/inorganic molecules and non-destructive medical diagnostics. Compound like As-H, H_2O, HCHO, CH_3COOH, CH_3, CCl_4 and various hydrocarbons show strong absorption in this range. Carbon (C) presence can also be detected in this spectral regime. Additionally, this wavelength range is very effective for latest medical treatment like, non destructive soft/hard tissue ablation, laser surgery for brain, nerve, eye, skin, corneal stroma etc. [3]. However, over the years it has been a challenge to develop simple but efficient scheme(s) to produce laser of sufficient power to address these applications. For this purpose, a high-power, compact, efficient and reliable continuous wave (CW)/pulsed laser sources in this mid-IR region is desirable. In this paper we propose a microstructured optical fiber (MOF) based mid-IR source generation covering 5 – 6.3 µm by exploiting nonlinear (NL) degenerate four wave mixing (D-FWM) effect. Chalcogenide glass is considered as fiber core material and commercially available CW CO laser of 10 W power as the pump (~ 5.6 µm). This superior D-FWM bandwidth (BW) is realizable through precise tailoring of the fiber's dispersion profile so as to realize positive quartic dispersion at the pump wavelength (λ_p). The fiber length (L) was also optimized to ~ 80 cm in order to achieve efficient phase matching between the propagating waves and the generated D-FWM signal.

2. Fiber design and results

Among various potential nonlinear phenomena [4], D-FWM is the dominant mechanism for wavelength translation provided certain phase matching condition is satisfied. Under the D-FWM process, pump photons of wavelength λ_p get converted to a signal photon ($\lambda_s > \lambda_p$) and an idler photon ($\lambda_i < \lambda_p$). In a highly NL single-mode fiber, the maximum frequency shift (Ω_S) depends on both the magnitude and sign of its GVD parameters [5]. On one hand, positive β_4 leads to broad-band and flat gain where as negative β_4 reduces the flatness and BW of the D-FWM output. Thus higher order dispersion management is very critical in such fiber designs [5].

To attain the goal, we propose an arsenic selenide (As_2Se_3) based MOF with 4 ring of hexagonally arranged holes, filled with polyethersulfone (PES) (cf. Fig. 1(a)). Fabrication compatibility of these two materials is already reported [2]. To limit confinement loss ($\alpha_c <$ 1dB/m) and to tune dispersion profile, we have chosen the rods (of radius r_3) in the 3rd cladding ring to be different from its surrounding rings. Design optimization for the targeted performance led to fiber parameters as Λ = 2.8 µm, $r_1 = r_2 = r_4$ = 0.59 µm and r_3 = 0.64 µm. To attain sufficient amplification factor ($AF = P_{out}/P_{in}$), over the targeted wavelength regime of 5 ~ 6.3 µm, we have assumed an input pump (λ_p ~ 5.6 µm) of 10 W power (P_0), whose wavelength approximately falls around the 2nd zero dispersion wavelength (λ_{ZD} = 5.676 µm) of the designed fiber. In order to suppress other potential NL effects, L was optimized to ~ 80 cm. Note that, we have calculated the input intensity as ~ 0.06 GW/cm^2, which is much lower than the threshold power for other NL effects to occur [4]. Dispersion (D) of the designed fiber is shown in Fig. 1(b). Additionally due to this tight confinement of light inside the As_2Se_3 core, the mode fields experience almost uniform nonlinearity (~ $1\text{x}10^{-17}$ m^2/W) during propagation and very low material loss (< 1dB/m in the targeted wavelength range).

In our initial simulations, we studied D-FWM performance under lossless, undepleted pump condition, where P_0 is assumed to be transferred only to λ_s and λ_i. We also show that launching of a weak idler (P_{in}) along with the pump improves the D-FWM efficiency through stimulated D-FWM. Variation of AF with generated spectrum at L = 50 cm is shown in Fig. 1(c). From this figure, we can interpret that, for 5.61 µm pump, the spectrum become broadest.

The central dip around pump is due to the linear growth ($AF \approx 1 + \gamma P_0 L$) of generated λ_s and λ_i at both sides of λ_p, where γ is the well known NL parameter [4].

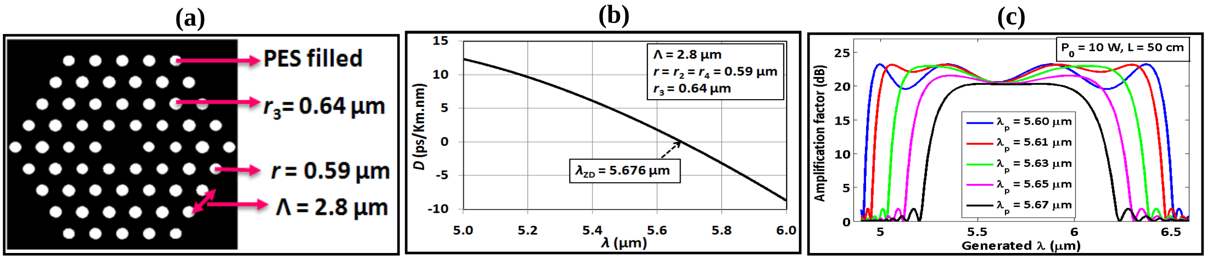

Fig. 1. (a) Cross section of the designed MOF. Cladding consists of 4 rings of PES rods (white circles) embedded in the As_2Se_3 matrix (black background); (b) Dispersion curve for optimum structure, λ_{ZD} = 5.676 μm; (c) Variation of *AF* for different λ_p neglecting pump depletion and material loss. With pumping at 5.61 μm (red curve), output spectrum is almost uniform with 3-dB BW ranging from 5 – 6.3 μm.

In the next step, assuming CW conditions, we have studied the complex amplitudes A_j (z) (j = p, i, s) and corresponding power (P_{out}) variations along the propagation distance (L) to study the effect of pump depletion and spectral dependence of material loss (α_j) by numerically solving the three coupled amplitude equations [5]. We have also optimized the P_{in} at ~ 15 mW to get maximum P_{out} for short length of fiber with sufficient BW and *AF*. As a sample, for one set of λ_s (6.3 μm) and λ_i (5.06 μm), variations in *AF* and P_{out} with L were studied (cf. Figs. 2(a) and 2(b)), which yielded optimum L = 78 cm. Even after inclusion of pump depletion and loss, average P_{out} > 4 W is achievable with a conversion efficiency > 40%. The entire signal spectrum is shown in Fig. 2(c). It can be seen that the spectral BW is very similar to the undepleted case with average $AF \approx 22\pm2$ dB. Note that, in this case the optimum L becomes ~ 80 cm. Such a fiber, if experimentally realized should be attractive as a mid-IR fiber optic light source covering a broad "molecular fingerprint regime".

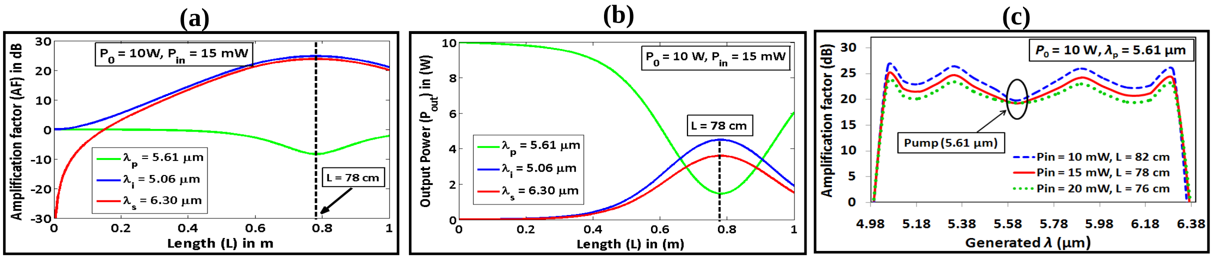

Fig. 2. (a) Variation of *AF* along length for λ_P, λ_s and λ_i including pump depletion and material loss; (b) Output power (P_{out}) variation; (c) Optimum output spectral 3-dB BW (5 – 6.3 μm) with pump depletion and loss for three different P_{in}. Maximum *AF* is ≈ 22±2 dB.

3. Conclusions and Acknowledgement

In this paper, we report a compact and efficient broad-band mid-IR fiber optic source design via wavelength translation through D-FWM process in a specialty chalcogenide MOF. Achievable amplification is shown to be ≈ 22±2 dB with a 5.61 μm pump of 10 W power from a ~ 80 cm long designed fiber for a broad spectral range of 5 – 6.3 μm. Average power conversion efficiency is > 40%. Thus our proposed fiber-based broad-band source, if gets fabricated, should motivate and open up new research avenues in mid-IR photonics for molecular spectroscopy as well as medical applications.

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