Near-IR to Mid-IR Supercontinuum Generation for High-Order Modes Using AsSe Multimode Fiber

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***Abstract*—We investigate the supercontinuum generation of the first four LP modes in an AsSe multimode fiber. Numerical results show that the supercontinuum spectra spanning from near-IR to mid-IR of high-order spatial modes are broader than that of the fundamental mode.**

1. INTRODUCTION

Supercontinuum (SC) generation has various applications including time-resolved excitation spectroscopy, bio-imaging and sensing [1]. In this regard, SC generation has been studied intensively since the early 1960s. SC can be generated by launching a short pulse into a nonlinear medium whereby its spectrum is broadened by a combination of nonlinear optical effects. The generation of SC has been experimentally demonstrated in photonic crystal fibers [2] and in a tapered conventional fiber [3]. By controlling the refractive index profiles of these fibers, their group velocity dispersion (GVD) could be tailored to optimize these nonlinear optical effects. In recent years, SC generation in few-mode fibers (FMF) and multimode fibers (MMF) has attracted increased attention, especially the performance of high-order modes. The modelling of nonlinear propagation of ultrashort pulses in MMF was studied in [4]. By using offset pumping, the SC of the LP_{11} and LP_{21} modes were generated in a PCF [5]. However, due to the shorter cut-off wavelength of higher-order modes, the output spectrum cannot extend beyond 1µm by this method.

Chalcogenide glasses are considered promising candidates for SC generation in both the near-infrared (NIR) and mid-infrared (MIR) region, due to their wider MIR transparency window and larger nonlinear refractive index over silica fibers. A SC bandwidth of over 10µm was generated in a step-index As_2S_3 MMF fiber [6]. By using suspended core AsSe fiber, a SC spanning from 1.7 to 7.5µm was also demonstrated [7]. Recently, an As_2Se_3/As_2S_3 multi-material tapered fiber was proposed to generate a SC spanning from 1.8 to 9.5µm with an average power over 30mW [8]. In the above works, the power of generated SC is mainly concentrated in the fundamental mode.

In this paper, we investigate the SC generation of the first four order of LP modes individually in an AsSe MMF. In order to observe the impact on SC generation of individual mode, a mode-selective photonic lantern (MSPL) was employed to excite a specific pump mode. A numerical simulation was carried out to model the pulse propagation of each LP mode in the fiber. According to our simulation results, the output spectra of high-order modes are broader than that of the fundamental mode, spanning from NIR toward MIR regime. Because of the pump wavelength are closer to the zero dispersion wavelength (ZDW) of high-order modes.

2. PRINCIPLE AND NUMERICAL RESULTS

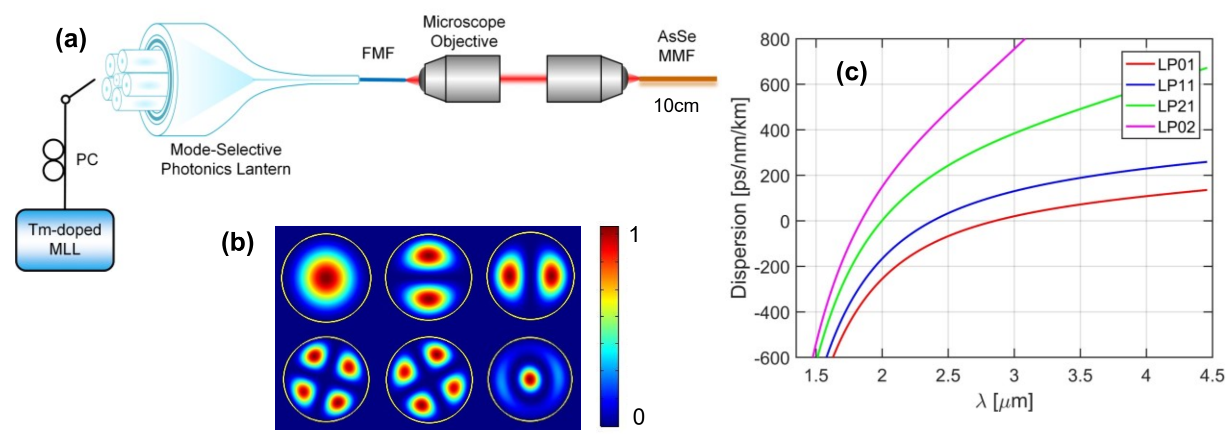

Fig. 1 (a) Schematic setup of high-order mode SC generation in the AsSe MMF; (b) calculated mode intensity profiles of the six lowest order spatial modes in AsSe MMF at a wavelength of 1950nm; (c) calculated dispersion curve of the first four LP modes.

The fiber we used to generate SC is a 10-cm long $As_{38}Se_{62}$ fiber rod whose diameter is only 4.8μm. The material nonlinear refractive index is $n_2=1.1\times10^{-17}m^2/W$. The ultra-high NA ensure it is a highly multimoded fiber. Fig. 1(a) shows the schematic setup. The pump source is a thulium-doped mode-locked fiber laser with a central wavelength of 1950nm. The pulse width is 500fs with a peak power of 5kW, and the repetition rate is 100MHz. We use a MSPL to convert the pump into different LP modes [9] and coupled into the chalcogenide fiber by a pair of 20X microscope objectives. The peak power of pulse that coupled into the fiber is estimated to be 2kW, with the majority of the loss being coupling loss. The mode intensity profiles of the six lowest order modes in AsSe MMF are shown in Fig. 1(b). We further computed the dispersion curve of four lowest order LP modes, the results are shown in Fig. 1(c). The ZDW of LP_{01}, LP_{11} LP_{21} and LP_{02} mode are 2.9, 2.4, 2 and 1.8μm, respectively. Since MSPL has high mode selectivity, we can assume only one LP mode was excited, so that the intermodal power transfer is negligible [4].

We simulated the spectrum evolution along the fiber for each LP mode individually based on generalized nonlinear Schrödinger equation (GNLSE) [1], the results are plotted in Fig. 2. We can clearly see that for LP_{01} and LP_{11} mode, the span of their spectrum are only 1μm and 1.5μm wide, because they are pumping in the strong normal dispersion regime. However, for LP_{21} mode, which is pumping at the ZDW, the span of output spectrum is nearly 2μm wide and covers the NIR and into the MIR region. For LP_{02} mode, where the pumping is in the anomalous dispersion regime, the generated SC is even broader. We also find the power of two sidebands are slightly larger than the pump wavelength because of modulation instability.

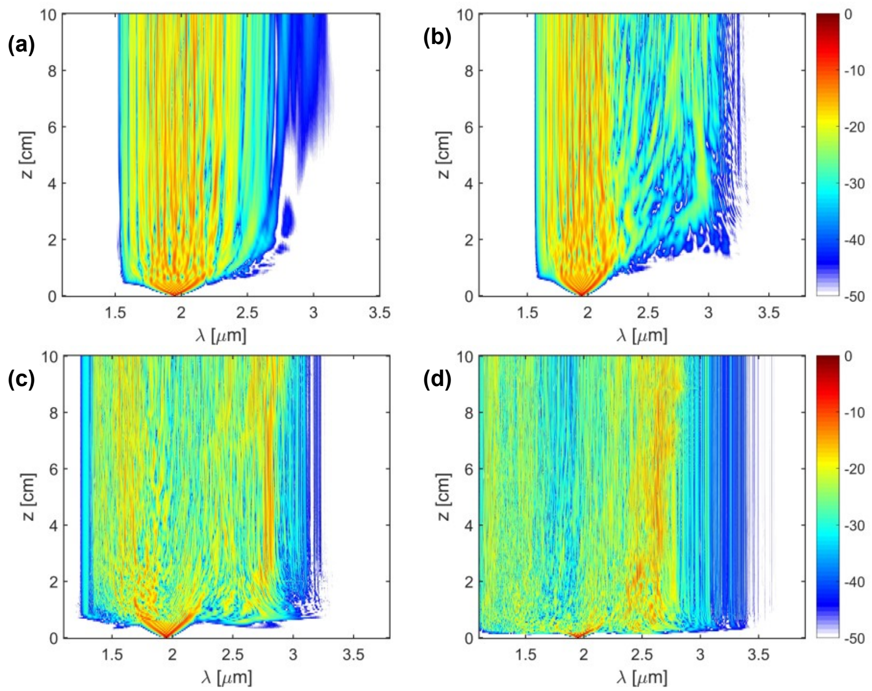

Fig. 2. Evolution of the spectral density along 10-cm long AsSe MMF for (a) LP_{01} (b) LP_{11} (c) LP_{21} and (d) LP_{02} mode.

3. CONCLUSION

We demonstrate the SC generation of the lowest four LP modes using an AsSe MMF. The SC with a span of nearly 2μm wide from NIR to MIR are generated for higher-order modes. Our scheme has great potential for the generation of broadband source of high-order modes.

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