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Mid-IR supercontinuum generation in a single-mode ZBLAN fiber by erbium-doped fiber laser

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Abstract. We present a compact broadband supercontinuum (SC) generation in a single-mode fluorozirconate $\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$ (ZBLAN) fiber pumped by femtosecond pulses from an erbium-doped fiber laser (EDFL). The femtosecond seed pulses are generated through passive mode locking using carbon-nanotubes-based saturable absorber in EDFL ring cavity. An SC spectrum spanning from 1100 to 3200 nm with a spectral flatness of <8 dB has been obtained successfully from a single-mode ZBLAN fiber. A piecewise linear relationship of SC spectrum bandwidth with input pulse power is observed. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.57.11.111804](https://doi.org/10.1117/1.OE.57.11.111804)]

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1 Introduction

Broad bandwidth laser sources have attracted extensive attention especially in the infrared region, owing to their numerous applications in the field of optical coherent tomography,¹ precision spectroscopy,² and optical frequency metrology,³ and remote sensing.⁴ New wavelengths generation capability beyond 2 μm , i.e., in mid-infrared (mid-IR) region, pushes the applications further in hyperspectral imaging,⁵ medical and biological systems,⁶ and LIDAR.⁷ In comparison with conventional IR light sources, such as lamps, synchrotron, and globars, fiber-based supercontinuum (SC) sources are attractive, offering stable design, simplicity, reliability, and compactness.

The major nonlinear phenomena associated with SC generation through extreme spectral broadening of optical seed pulse are modulation instability (MI), self-phase modulation (SPM), stimulated Raman scattering (SRS), cross-phase modulation, and four-wave mixing (FWM). SPM plays a dominant role in spectral broadening processes when the fiber is pumped with femtosecond pulses in normal dispersion region, while soliton self-frequency shifts and soliton fission are responsible for SC generation in anomalous dispersion region. When it comes to relatively longer pulses, such as in picosecond and nanosecond scale, spectral broadening is dominated by FWM in normal dispersion, and SRS and MI in anomalous dispersion region, respectively.^{8–10} For efficient and broad SC generation, activation of these nonlinear properties is needed, which is possible only by giving high input powers. Achieving high power with CW lasers is a quite challenging task as compared to pulsed lasers. Such high-power laser pulses can be obtained using mode-locking technique on CW laser. In this work, carbon-nanotubes (CNT) type of SA has been chosen for experiments to achieve passive mode locking because of its attractive properties, such as cost-effective production, ultrafast recovery time, and ease of fiber integration.^{11–14} For a few decades,

intensive research has been done on the fiber-based SC sources, which mainly focuses on the silica-based fibers.¹⁵ However, the SC spectrum is limited to 2.5 μm due to intrinsic losses of silica substrate.¹⁶ Therefore, to generate mid-IR SC beyond 2.5 μm , fibers with low transmission loss in the mid-IR region, such as soft glass fibers composed of tellurite, fluoride, and chalcogenide glasses, are required, and alternatively, there was an approach called hollow-core fiber to reduce the silica material absorption significantly.^{15,17,18} Among all heavy metal fluoride fibers, $\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$ (ZBLAN) has been adopted due to its high glass stability, technology maturity, and transparency in mid-IR region.¹⁹ The typical zero-dispersion wavelength (ZDW) of the ZBLAN fiber lies between 1.65 and 1.9 μm .²⁰ SC generation dynamics depends on the pump pulse duration, nonlinearity coefficient of the fiber, and the relationship between the pump wavelength and the ZDW of a nonlinear fiber.²¹

To date, mid-IR SC generation that involves multistage SC generation and multistage amplification has been adopted widely. The system in general is complex and suffers poor stability. Here, we reduced the complexity and improved the stability and compactness of the system using single-stage SC generation approach. In this article, for the first time to our knowledge, we demonstrate a CNT-based passively mode-locked femtosecond erbium-doped fiber laser (EDFL)-based SC generation in ZBLAN fiber. The CNT-based mode locking has achieved a pulse width of 620 fs with a repetition rate of 18 MHz at a center wavelength of 1565 nm. A single-stage amplification is employed on mode-locked pulses and the trend of spectral broadening inside the ZBLAN fiber is studied experimentally at different input pulse power levels. The study of SC generation inside the ZBLAN fiber at high input pulse powers is limited by the output power limitation of erbium-doped fiber amplifier (EDFA) and limitation of optical spectrum analyzer (OSA) wavelength measurement. We have successfully demonstrated an SC spectrum generation from a ZBLAN fiber covering a bandwidth of

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Fig. 1 Experimental schematic of mid-IR SC generation from ZBLAN fiber. WDM, wavelength-division multiplexing; EDF, erbium-doped fiber; ISO, isolator; PC, polarization controller; CNT-SA, carbon-nano-tube-based saturable absorber; OC, output coupler; EDFA, pulsed erbium-doped fiber amplifier; and ZBLAN, $\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$.

2100 nm extending from 1100 to 3200 nm at an input pulse power of 25 dBm. We achieved a smooth spectrum with spectral flatness of <8 dB. A piecewise linear relationship of SC spectrum bandwidth with the input pulse power is observed.

2 Experimental Setup

Figure 1 shows the experimental schematic of mid-IR SC generation from ZBLAN fiber using CNT-based passively mode-locked femtosecond EDFL. The EDFL ring cavity is built in our laboratory. A 0.6-m-long erbium-doped fiber (EDF) is pumped by a 976-nm laser diode source through a 980/1550-nm wavelength-division-multiplexing (WDM) coupler. A polarization controller (PC) is inserted in the cavity to adjust and optimize the mode-locking condition. Also, an optical isolator is inserted to ensure unidirectional optical signal propagation in the cavity. The 10% of the optical power is extracted from the cavity through the 90/10 optical coupler as the mode-locked laser (MLL) output. The EDF, which is used in this experiment, is a commercial product (LIEKKI Er110) with a peak core absorption of 110 dB/m and a mode-field diameter around $6.5\ \mu\text{m}$ at 1530 nm. The modulation depth and the nonsaturable absorption of CNT-SA used in this experiment at 1560 nm are 8% and 27%, respectively. All the remaining fibers used in the cavity are standard single-mode fibers and the overall length of the cavity is around 5 m.

2.1 Results and Discussion

2.1.1 Characterization of mode-locked laser pulse

The spectral and temporal characteristics of MLL pulse are characterized by an OSA and a 2-GHz photodetector followed by 350-MHz oscilloscope, respectively. Figure 2 shows the characterization of CNT-SA passively MLL pulse. Figure 2(a) shows the optical spectrum of MLL pulse, which is centered at $\sim 1565\ \text{nm}$ with a 3-dB bandwidth of $\sim 5\ \text{nm}$. Figure 2(b) shows the autocorrelation trace of MLL pulse with sech^2 fitting and it has pulse width of 620 fs at its full width half maximum value. Figure 2(c) shows the

oscilloscope trace of output MLL pulse train with a pulse repetition rate of 18 MHz. The 10% output pulse average power and pulse peak power are observed as 0.21 mW and 18.5 W, respectively, at stable mode-locked condition.

2.1.2 Femtosecond mode-locked laser pulse amplification and mid-IR supercontinuum generation from ZBLAN

At an input pump power of 126 mW, a stable and clean MLL pulse emission is observed from output of the ring cavity. However, the measured 10% output average power (0.21 mW) of the MLL pulse is not significant enough to launch directly into ZBLAN to observe the spectral broadening phenomena. To observe the spectral broadening phenomena efficiently from ZBLAN fiber, the output of MLL pulse is amplified using a commercially available EDFA. As shown in Fig. 1, isolators are connected at both the input and output of the EDFA to protect the EDFA from back reflections and to maintain the stability of MLL cavity. The output of EDFA is connected to the 25-m-long ZBLAN fiber through an isolator, and the SC spectrum from ZBLAN fiber is observed by varying input pulse power from 10 to 25 dBm. The ZBLAN fiber has a core/cladding diameter of $6/125\ \mu\text{m}$, NA of 0.26, and ZDW is at $\sim 1.6\ \mu\text{m}$. We have avoided the multistage amplification and subband SC generation as reported in previous studies to generate broad SC generation toward mid-IR region.²⁰ In our approach, we used only a single stage of amplification and generated SC directly by launching amplified pulse into ZBLAN fiber without any intermediate stages of SC generation, such as first launching into a small piece of highly nonlinear fiber or single-mode fiber or EDF and thereby launching into ZBLAN fiber, which makes our setup more environmentally stable, economical, and compact.

Figure 3 shows the variation of output SC spectrum from ZBLAN fiber for different input powers. To observe the spectral broadening phenomena and the bandwidth variation of SC generation from ZBLAN fiber with respect to input power variation, the pulse power is varied from 10 to 25 dBm. Three different OSAs (450 to 1750 nm OSA1, 1200 to 2400 nm OSA2, and 1200 to 3400 nm OSA3) have been used to analyze the SC spectrum generated from ZBLAN fiber. All the three OSAs are maintained at the same input conditions, and the intensity mismatch is minimized using subtraction method at the intersecting wavelength of the OSAs. It is observed that the spectral broadening followed by SC bandwidth increases with the increase in the input pulse power. Also, over the variation of input seed pulse power from 10 to 25 dBm, the observed average power loss in the 25-m length of ZBLAN fiber is $\sim 7\ \text{dB}$. The flat and maximum SC bandwidth of 2100 nm extending from 1100 to 3200 nm is observed at an input power level of 25 dBm. For all the input powers, the spectrum was bidirectionally broadened both to the near- and mid-IR region. The dip that was observed in the spectrum at around 2700 nm corresponds to OH^{-1} ions absorption in the ZBLAN fiber and unpurged detection of long wavelength OSA. The further study of SC spectrum from ZBLAN fiber at higher powers is limited by the EDFA output power and OSA wavelength range.

The femtosecond pulses experience normal dispersion in the ZBLAN fiber as the seed pulse wavelength (1565 nm) is below the ZDW (1600 nm) of ZBLAN. Therefore, initially

Fig. 2 (a) MLL pulse output spectrum with 3-dB bandwidth of ~ 5 nm, (b) autocorrelation trace with sech² fitting of MLL pulse width of 620 fs, and (c) oscilloscope trace of MLL pulse train with a repetition rate of 18 MHz.

Fig. 3 Variation of SC spectrum generation from ZBLAN with respect to different input powers.

the spectral broadening inside the ZBLAN is dominated by the SPM and soliton-frequency shift, and as the pulse propagates further inside the fiber, the SC spectrum broadening toward longer wavelength side is dominated by the soliton

fission. At all the input pulse powers, there appears a residual peak in the output SC spectrum at around 1550 nm, which is appearing from the amplification of seed pulse. When comes to the different peaks in the output, SC spectrum corresponds

Fig. 4 SC spectrum bandwidth variation with respect to the input pulse power.

to the input pulse powers at 10 and 15 dBm and is attributed by the weak SPM and soliton-frequency shift effect, which disappears at high input pulse powers as the SPM and soliton-frequency shift phenomena become stronger. Strong SPM processes enhance the transfer of energy away from pump peak and thereby decrease residual pump light in the spectrum. Thus, a flatter spectrum is generated by pumping femtosecond pulses in normal dispersion region.

Figure 4 shows the variation of SC spectrum bandwidth from ZBLAN fiber output with respect to the input pulse power. From the graph, a piecewise linear relationship of SC spectrum bandwidth increment with input power is observed, and to make this relationship more reliable, we have added 5% error bar to the data points. This knowledge of bandwidth versus input power relationship help us to estimate the amount of power that we need to pump a ZBLAN fiber to generate a particular bandwidth of SC spectrum. Based on the piecewise linear relationship, it is observed that the ZBLAN generates an SC spectrum bandwidth at a rate of ~ 80 nm/dB when the input power is < 19.5 dBm and ~ 200 nm/dB in high-power region (input power > 19.5 dBm). In our case, the study of SC generation at further higher powers is limited by the EDFA maximum power limitation and the OSA wavelength range limitation.

3 Conclusion

We demonstrated a flat and broad mid-IR SC generation with spectrum bandwidth of 2100 nm spanning from 1100 to 3200 nm in a single-mode ZBLAN fiber pumped by a 620-fs EDFA pulses at an input power of 25 dBm. CNT-SA-based passive mode-locking technique has been used to achieve a femtosecond seed pulse to pump the ZBLAN fiber. The spectral broadening phenomena within the ZBLAN fiber are observed for different input powers and also a piecewise linear relationship of SC spectrum bandwidth with input pulse power variation is observed.

Disclosures

This article is the revised version of our previous work, which was published in the SPIE Photonics West conference proceedings.

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