Mid-infrared supercontinuum generation to 4.5 μm in ZBLAN fluoride fibers by nanosecond diode pumping

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A mid-infrared supercontinuum (SC) is generated in ZBLAN ($ZrF_4-BaF_2-LaF_3-AlF_3-NaF\ldots$) fluoride fibers from amplified nanosecond laser diode pulses with a continuous spectrum from ~0.8 μm to beyond 4.5 μm. The SC has an average power of ~23 mW, a pump-to-SC power conversion efficiency exceeding 50%, and a spectral power density of ~−20 dBm/nm over a large fraction of the spectrum. The SC generation is initiated by the breakup of nanosecond laser diode pulses into femtosecond pulses through modulation instability, and the spectrum is then broadened primarily through fiber nonlinearities in ~2–7 m lengths of ZBLAN fiber. The SC long-wavelength edge is consistent with the intrinsic ZBLAN material absorption.

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We generate, for the first time to our knowledge, the broadest supercontinuum (SC) extending from ~0.8 μm (near-IR) to beyond 4.5 μm (mid-IR) in ZBLAN ($ZrF_4-BaF_2-LaF_3-AlF_3-NaF\ldots$) fluoride fibers. Nanosecond laser diode pulses are amplified by multiple stages of an erbium-doped fiber amplifier (EDFA) and broken up into femtosecond pulses by modulation instability (MI) in ~1 m standard single-mode fiber (SMF).[1,2] The SC spectrum is broadened in the ZBLAN fiber primarily by self-phase modulation (SPM) and stimulated Raman scattering and is smoothed owing to the range of intensities in the pump pulses.[1–4] The use of ZBLAN fibers with a long cutoff wavelength (2.75 μm) allows the SC edge to be extended to 4.5 μm, which is consistent with the intrinsic ZBLAN material absorption.

An all-fiber, mid-IR light source can provide significant advantages over existing IR laser light sources. Typically, mid-IR light is generated by using optical parametric oscillators or quantum cascaded lasers.[5] In contrast, the fiber light source operates at room temperature with no moving parts, and the fibers have a high power damage threshold, facilitating power scaling.

SC generation using various pump lasers has been widely studied in different types of fiber. For example, SCs ranging from ~0.8 to 2.6 μm have been generated in a highly nonlinear, silica fiber by a mode-locked femtosecond laser.[6] Amplified laser diode pulses have also been used to generate SCs from 0.9 to 1.7 μm[7] and from ~0.8 to 3.0 μm in a highly nonlinear silica fiber.[2] To generate a SC to the mid-IR, fibers having lower loss in the mid-IR windows are required.

Fluoride fibers have the lowest loss coefficient of mid-IR fibers in the 2–5 μm region,[8] and SC generation in ZBLAN fibers out to 3.4 μm was achieved with femtosecond laser pumping.[9] Our experiments, using ZBLAN fibers with a long cutoff wavelength and nanosecond pulses, lead to a simple system for generating a SC out to 4.5 μm.

A two-stage approach is used to optimize SC generation. The first stage comprises a 1–2 m length of SMF, which is spliced to the output of the EDFA. By pumping the SMF in the anomalous dispersion region, the MI can be phase matched to break up the nanosecond pulses into femtosecond pulses,[2] which eliminates the need for mode-locked lasers. The second stage consists of a ~2–7 m ZBLAN fiber in which the SC is broadened by fiber nonlinearities.

The experimental setup is illustrated in Fig. 1. The setup emulates a Q-switched laser system. The system stores energy between pulses by using the long, upper-state, lifetime of the EFDA, which allows a laser diode driven with a low duty cycle to produce a larger energy per pulse. A distributed feedback laser at 1553 nm is driven by a pulse generator to provide the seed light with ~2 ns pulse width at 5 kHz repetition rate. The light is amplified in a low-noise EDFA preamplifier followed by an electro-optic modulator synchronized to the pulse generator to suppress the amplified spontaneous emission. The modulator loss is compensated by the mid-stage EDFA, and the output is bandpass filtered before

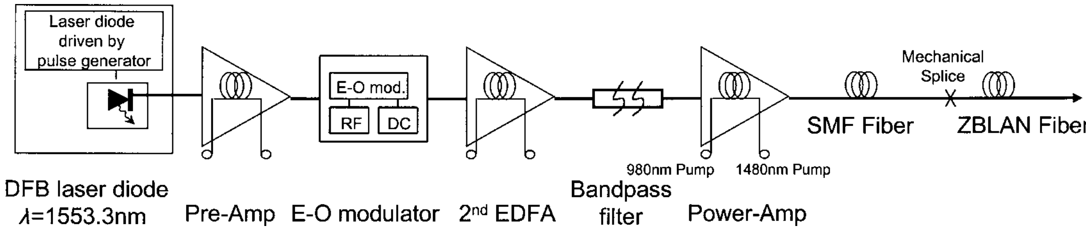

Fig. 1. Experimental setup for 2 ns laser diode pulses amplified in multiple stages of EDFAs.

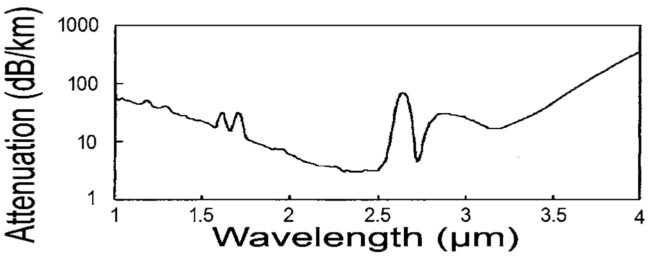

Fig. 2. Attenuation loss (dB/km) for the third ZBLAN fiber (FL#3) with a cutoff wavelength at 2.75 μm.

launching into the final stage power amplifier. The light is boosted in the power amplifier to a peak power approaching ~4 kW and an average power of ~40 mW.

Three fibers are used in the experiments with a cladding diameter of 125 μm and with the following characteristics (fiber name, core diameter, cutoff wavelength): (a) FL#1, 5.7 μm, 1.25 μm; (b) FL#2, 8.5 μm, 1.75 μm; and (c) FL#3, 7 μm, 2.75 μm. According to Ref. 10, the material zero-dispersion wavelength in ZBLAN is ~1.65 μm. The loss curve of FL#3 is shown in Fig. 2. The attenuation out to 4 μm is measured to be <1 dB/m. The loss in FL#1 and FL#2 is similar to FL#3 up to ~2.5 μm (<0.1 dB/m) but increases thereafter owing to the bend-induced loss.

During the test, light from the SMF fiber is mechanically spliced to the ZBLAN fiber with a coupling loss of ~1.5 dB. Mechanical coupling also ensures single-mode excitation in the ZBLAN fiber. A spectrum ranging from 700 to 1700 nm is measured by an optical spectrum analyzer, while the longer wavelengths are measured by a grating spectrometer, using a cooled InSb detector. The interior of the spectrometer is purged by gaseous nitrogen to minimize the atmospheric water and CO_2 absorption.

Figure 3(a) shows the SC spectrum of ~7 m of FL#3 following an approximately 1 m length of SMF at 4 kW of peak input power. A SC ranging from ~0.8 μm to more than 4.5 μm is observed with the time-averaged spectral power density of ~−20 dBm/nm over a large fraction of the spectrum. The SC average power is ~23 mW with the conversion efficiency from the pump power exceeding 50%. The peak at 1553 nm is the residual pump from the laser diode, and the features around 980 nm are due to the undepleted forward pump of the EDFA. The long-wavelength edge 20 dB down is measured to be at ~4.3 μm, although the longest measured wavelength extends well beyond 4.5 μm.

A SC spectrum generated from ~4.5 m of FL#3 following a 1 m SMF is illustrated in Fig. 3(b). The long-wavelength edge of the spectrum is slightly shorter than the spectrum of Fig. 3(a), but otherwise the two spectra are similar. Therefore much of the SC spectrum is generated within the first ~4.5 m of the ZBLAN fluoride fiber.

To obtain the broadest SC spectrum, the length of each stage should be optimized. Figure 4(a) shows the spectrum for varying lengths of first-stage SMF followed by a 3 m length of FL#2. As can be seen, 1 m of SMF leads to the broadest SC spectrum for a peak pump power in the range 3–4 kW. Also, SC spectra generated from 1 m of SMF followed by different lengths of FL#3 are illustrated in Fig. 4(b). The SC spectrum after 4.5 m of ZBLAN fiber already extends beyond 4.4 μm. Finally, Fig. 4(c) shows the SC spectra for different pump powers in 1 m of SMF plus 2 m of FL#3. The spectrum is generated by an ~1.2 kW peak pump power and fills in as the power further increases.

The spectral width observed in the ZBLAN fiber is consistent with Mi-induced pulse breakup followed by SPM-dominated broadening. Autocorrelation measurements and simulations show that the peak intensity of the pulses after the first stage increases approximately fourfold to ~15 kW with a pulse width of

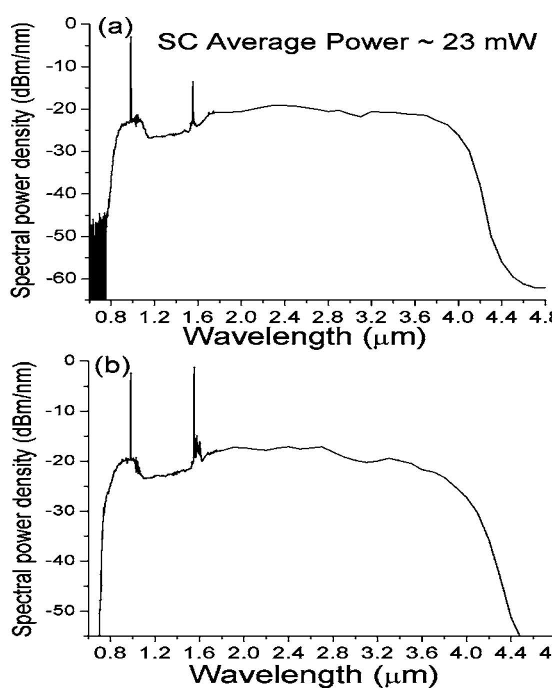

Fig. 3. SC Spectrum from ~1 m of SMF followed by (a) 7 m and (b) 4.5 m of FL#3 fluoride fiber.

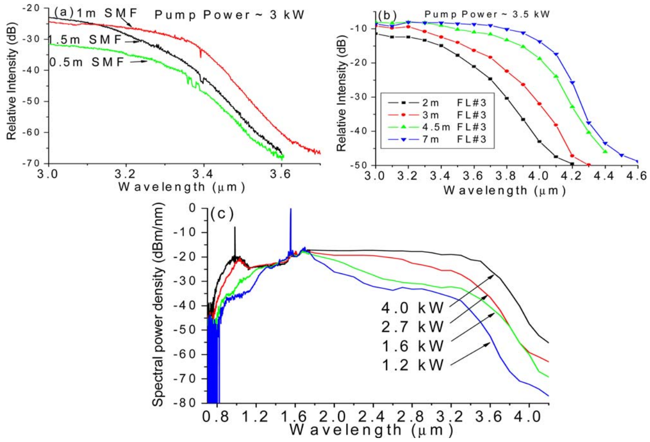

Fig. 4. (Color online) Optimization of SC generation by varying different parameters. (a) Various lengths of the first-stage SMF fiber followed by 3 m of FL#2; (b) various lengths of the second-stage ZBLAN FL#3 fiber following 1 m of SMF; and (c) various pump power levels in 1 m of SMF plus 2 m of FL#3 fiber.

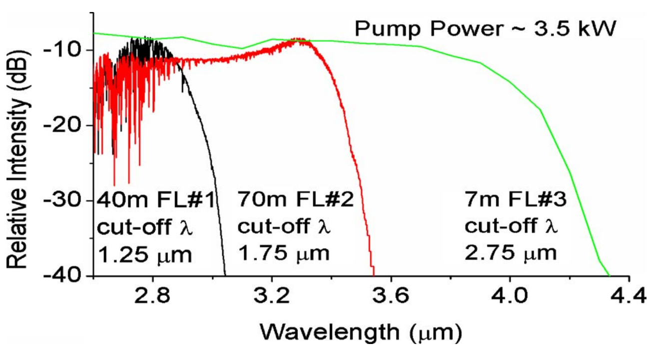

Fig. 5. (Color online) Spectrum of the SC long-wavelength side for three different ZBLAN fibers.

~150 fs. The spectrum broadening through SPM, ignoring fiber losses, can be approximated by $\delta f \approx n_2 P L_{\text{eff}} / A_{\text{eff}} \lambda \tau$, where n_2 is the nonlinear refractive index of the fiber core, A_{eff} is the effective mode area, and τ is the pump pulse width. The nonlinear refractive index n_2 is $\sim 2.1 \times 10^{-16}\ \text{cm}^2/\text{W}$,[11] with $A_{\text{eff}} \sim 38\ \mu\text{m}^2$ for ZBLAN FL#3. So the SPM-generated frequency shift is $\sim 1.4 \times 10^{14}$ Hz in a 4 m length of FL#3, with the corresponding short-wavelength side at ~0.9 μm and long-wavelength side at ~5.6 μm for 1.55 μm pumping. The measured edge at 4.5 μm may be due to the fiber loss, as described below. The smoothness of the SC spectrum may be due to the range of the intensities in the pulse; i.e., different temporal parts of the pulse contribute to different parts of the spectrum.

The long-wavelength edge of the SC is limited by the loss in the ZBLAN fiber. For fibers with cutoff wavelength $< \sim 2\ \mu$m, the long-wavelength loss is primarily due to the bend-induced loss. In particular, bend-induced loss is known to be wavelength dependent and to increase rapidly with increasing wavelength.[12] The long-wavelength spectra of the SC generated in three fibers with different cutoff wavelengths are shown in Fig. 5. As the cutoff wavelength increases from 1.25 to 2.75 μm, the long-wavelength edge of the SC spectrum pushes out from ~3 to ~4.5 μm.

The SC long-wavelength edge of FL#3 at ~4.5 μm [Fig. 3(a)] is consistent with the intrinsic ZBLAN material loss. For example, the attenuation is measured to be 1 dB/m at 4.3 μm, 2.25 dB/m at 4.5 μm, and 8 dB/m at 4.8 μm in a multimode ZBLAN fiber with similar glass compositions. It should be noted that this edge is primarily due to the intrinsic loss associated with zirconium and aluminum. Therefore fluoride glass compositions that avoid zirconium and aluminum could potentially generate SC out to 5 μm and beyond.

In summary, we have generated what is to our knowledge the broadest mid-IR SC reported to date in ZBLAN fluoride fibers produced by laser diode pumping. The SC extended to 4.5 μm with an average power in the SC of ~23 mW with a power conversion efficiency over 50%. The SC is induced through MI in ~1 m of SMF fiber, and the long-wavelength edge is limited by the ZBLAN fiber loss. The SC edge can be potentially extended beyond 5 μm with modified fluoride glass compositions. The SC average power can also be scaled up by increasing the pulse repetition rate while maintaining approximately the same peak power and pulse width.

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