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Highly Stable, All-fiber, High Power ZBLAN Supercontinuum Source Reaching 4.75 μm used for Nanosecond mid-IR Spectroscopy

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Abstract: We demonstrate compact all-fiber mid-IR supercontinuum generation up to 4.75 μm with 1.2 W output power during hundreds of hours. This source is applied to upconversion spectroscopy using the energy corresponding to a single pulse.

OCIS codes: (060.4370) Nonlinear Optics, fibers; (320.6629) Supercontinuum generation.

1. Introduction

Since the first commercial broadband visible supercontinuum (SC) sources came on the market a decade ago the adaptation of these sources has penetrated many fields of sensing and biooptics and particularly the field of fluorescence microscopy has been revolutionized by the implementation of simple, rugged, turn-key SC systems. Now the emergence of supercontinuum sources in the mid-IR heralds a similar revolution in mid-IR sensing. Here we demonstrate a high power compact all-fiber supercontinuum source which extends the bandwidth available to ZBLAN ($\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$) based supercontinuum sources significantly and we prove the reliability of the source by running the source continuously at maximum power for hundreds of hours. The high intensity and spatial coherence of such SC sources opens up a wide range of new possibilities for applications in mid-IR sensing and microscopy as we indicate by using this source to show the road to nanosecond spectroscopy.

2. Supercontinuum source

A supercontinuum source comprises a pump laser which emits short high intensity pulses which are subsequently broadened in a nonlinear fiber to generate a very high intensity light in a wide spectrum. In order to generate supercontinuum at wavelengths longer than approx 2.5 μm it is necessary to use a nonlinear fiber made from different glasses than silica and typical choices for this are ZBLAN, telluride or chalcogenides. All these glasses have relatively low melting points compared to silica and when designing a high power (>1W) system utilizing such fibers it is important to limit the amount of heating occurring in the nonlinear fiber to avoid fiber damage and to distribute the losses as much as possible so that cooling becomes simpler. In order for this to be possible it is desirable to have a nonlinear fiber of at least a few meters with low transmission losses. The lowest transmission losses of all mid-IR fibers have been demonstrated in ZBLAN fibers [1] and this, combined with the relatively high stability of ZBLAN glass, has made ZBLAN a popular choice for mid-IR supercontinuum sources. Supercontinua spanning up to 6.28 μm has been demonstrated using femtosecond pump pulses with megawatt peak power in a few centimeters of ZBLAN fiber [2], but this is an approach which could only be used to generate a low average power continuum otherwise the nonlinear fiber would overheat. For high average power sources longer fibers must be used to distribute the thermal load and for these the material absorption of ZBLAN, which rises sharply above 4.5 μm has previously limited supercontinuum based on long ZBLAN fibers to a maximum wavelength of 4.5 μm [3]. Here we have used a highly optimized pump system combined with a short ZBLAN fiber to increase the spectrum by 250 nm to 4.75 μm and to our knowledge this is the longest wavelength high power supercontinuum generated in a ZBLAN fiber to date.

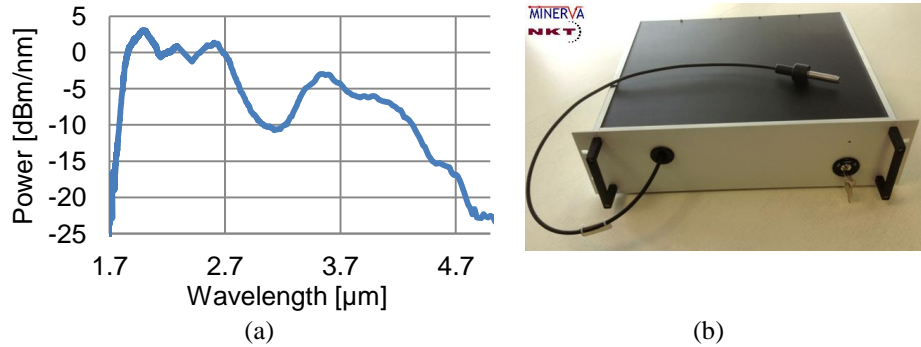


Fig.1(a) Spectrum of the mid-IR supercontinuum source. (b) Compact 1.2W mid-IR supercontinuum source from NKT Photonics

Our system which is based on a combination of 1550 nm pumping and thulium doped fiber similar to that demonstrated by Geng et al. [4] utilizes an optimized pump system and an optimized ZBLAN fiber design and few meter nonlinear fiber length to generate up to 1.2 W in a 1.75-4.75 μm spectrum in 3 ns pulses with a repetition rate of up to 350 kHz. The power above 2.0 μm is up to 775mW and the power above 3.5 μm is up to 120 mW. The output power can be tuned freely between 60 mW and 1.2 W by adjusting the pulse repetition rate between 30 and 350 kHz. The pulse energy falls off slightly at the lower repetition rates due to increased amplified stimulated emission (ASE) in the pump system. The system is all-fiber and delivers simple turn-key operation integrated in a compact package as seen in figure 1 b.

2. Power stability

As the name implies the so-called soft glasses has lower chemical and thermal resistance than that silica and there has therefore been some doubt in the community if supercontinuum systems based on these glasses will ever provide reliable high power operation. In order to address this concern the system was run continuously at maximum output power for 330 hours without significant degradation after which the system was collimated and run for another 160 hours. A log of the development in output power over time after collimation can be seen in figure 3, which shows that after an initial heat-up of the system, the power stabilizes. A similar system with lower pulse repetition rate and an output average power of only 90 mW was run for over 2000 hours, also without showing signs of degradation.

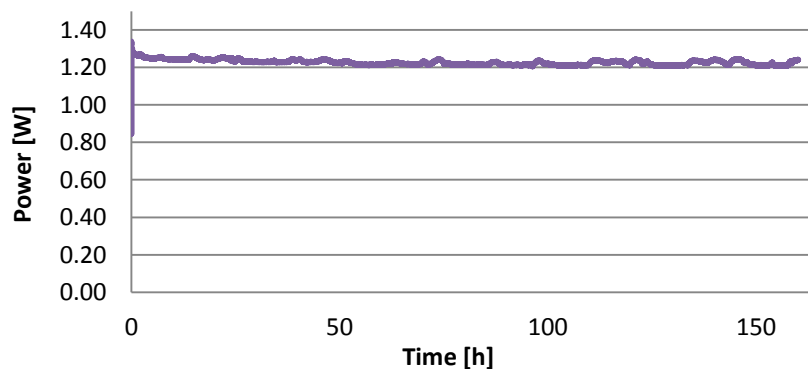


Fig.2 Power stability of the 1.2W mid-IR supercontinuum source running at constant pump current

To the knowledge of the authors this is the first time that hundreds of hours of stable uninterrupted operation of a high power supercontinuum source based on soft glasses has been documented. This demonstrates that there is no reason to expect that the reliability of the mid-IR sources will be lower than that of visible supercontinuum sources which are currently being adopted by the industry.

3. Ultrafast spectroscopy

The high power available in a single pulse allows for ultrafast spectroscopy applications. To demonstrate this, the light source is used in conjunction with a system designed to convert mid-infrared light to near visible wavelengths [5]. The wavelength conversion happens by mixing mid-infrared radiation with a 1064 nm laser inside

a periodically poled Lithium Niobate crystal. By placing the Lithium Niobate inside the laser cavity a high circulating laser field can be achieved (~ 100 W). This gives rise to quantum efficiencies for the upconversion approaching 20 %. To demonstrate the possibility of ultrafast spectroscopy we set up a 10 cm long gas cell with 1 atm methane. In this demonstration we set up the camera to only capture an amount of light corresponding to a single pulse of supercontinuum light. By setting the camera integration time to 0.47 ms and the SC pulse repetition rate to the 30 kHz minimum we captured only 14 pulses and simultaneously used optics to dampen the light to $1/14^{\text{th}}$ of the power, thus yielding the energy per frame corresponding to only a single pulse. Since the upconversion system detects one wavelength in the center of the image, and longer wavelengths away from the center, we can in a single image see the transmission spectrum of methane with the nanosecond time resolution corresponding to the duration of a single pulse.

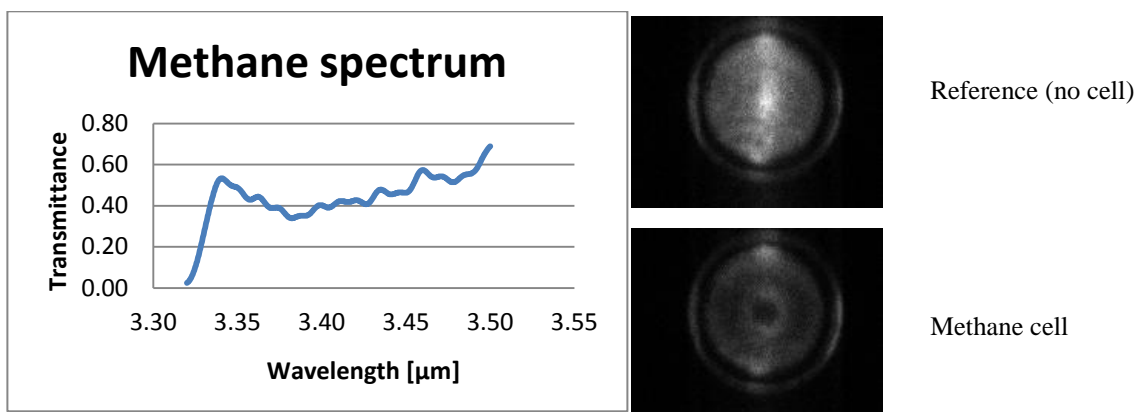


Fig. 2. Transmission of continuum light source through methane gas cell. Left shows methane transmission spectrum as calculated from the Hitran database. Right shows images with and without a methane gas cell in the beam path. The images have spectral information showing strong absorbance in the center of the image (3.32 μm), higher transmission in a small circle (3.34 μm) following the expected transmission spectrum.

4. Conclusion

We have demonstrated an all-fiber turn-key high power ZBLAN based supercontinuum source which delivers 1.2 W output power and pushes the long wavelength edge up to 4.75 μm . We prove the reliability of mid-IR supercontinuum sources by running this source continuously a full power for hundreds of hours. In the near future this highly reliable source will be combined with a mid-IR acousto optical filter (AOTF) to yield a high intensity light source freely tunable in the 2–4.5 μm band which will be applied to cancer diagnostics all as part of the EU funded FP7 project MINERVA [6]. Finally we demonstrate the potential of recording an absorption spectrum in a few nanoseconds by combining this high pulse energy source with a novel upconversion technique in order to make wideband spectral recording using light corresponding to a single laser shot.

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