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Experimental demonstration of multiwatt continuous-wave supercontinuum tailoring in photonic crystal fibers
Spectrally tailored mid-infrared super-continuum generation in a buried waveguide spanning 1750 nm to 5000 nm for atmospheric transmission

J. McCarthy,1 H. Bookey,1,2 S. Beecher,3 R. Lamb,4 I. Elder,4 and A. K. Kar1

1Institute of Photonics and Quantum Sciences, School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh EH14 4AS, United Kingdom
2Fraunhofer Centre for Applied Photonics, 347 Cathedral St., University Centre, Glasgow G1 2TB, United Kingdom
3Optoelectronics Research Centre, University of Southampton, SO17 1BJ, United Kingdom
4SELEX ES, Crewe Toll, 2 Crewe Road, Edinburgh EH5 2XS, United Kingdom

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We show how nonlinear spectral broadening in a buried chalcogenide mid-infrared waveguide can be used to reshape the spectrum of a femtosecond pulse train at 4260 nm in order to reduce the effects of atmospheric absorption due to carbon dioxide. The nonlinear spectral broadening results in the source with ~20 dB spectral width spanning over 3500 nm, from 1700 nm to 5200 nm. This represents a potential route to tailored sources for long-range mid-infrared applications. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4824358]

The mid infrared atmospheric transmission window from 2 to 5 μm is of interest for biomedical,1,2 directed infra-red counter-measures,3 and gas sensing applications4,5 and consequently, there is motivation for the development of broadband sources in this region. Super-continuum (SC) generation in optical fibers and waveguides is a mature field and is well understood.6,7 SC extending into the mid infrared spectral region is of interest for spectroscopy, nonlinear microscopy, optical metrology, optical coherence tomography, and frequency comb generation.

For efficient atmospheric transmission in the 3–5 μm window, it has previously been proposed to use the spectral shaping effects of self-phase modulation (SPM) to avoid the losses associated with carbon dioxide absorption at 4.25 μm.8 Carbon dioxide absorption is the main contributor to transmission loss in the 2–5 μm window and by pumping a nonlinear material at a wavelength centered on a CO2 absorption feature SPM can tailor the source spectrum such that the majority of the spectral energy density is distributed to other wavelengths within the transmission window. In this letter we present an experimental realization of this concept. Nonlinear spectral broadening of pulse trains having pump wavelengths beyond 4 μm has only been realized in bulk substrates9 we present observations of supercontinuum generation in a guided wave device using a pump wavelength longer 4 microns.

SC sources are readily available and their long wavelength limits are often determined by the material linear transmission spectrum. Using chalcogenide glasses, it is possible to exploit excellent long wavelength transmission properties that are coupled with a high optical nonlinearity.10 The progress in materials science over the last few years has meant that chalcogenide glasses of high optical quality are now commercially available and have been developed for fiber drawing applications.11 There are several reports on the fabrication of non-silica fibers and fiber tapers for octave spanning SC extending into the mid infrared.12–15 However, chalcogenide fibers are difficult to fabricate with low loss and are difficult to handle, although there is a recent report of a scheme to encase a chalcogenide nano-taper with a silica over-cladding.16 For short pulse durations it is not necessary to have the long interaction lengths enabled by a fiber platform for optimum SC generation17 and an optical chip would benefit integration with other components. Many of the techniques used to make integrated chalcogenide waveguides rely on multi-step deposition18 or embossing19 processes which have their own limitations. On the other hand, direct laser writing has been successfully utilized to fabricate buried singlemode waveguides in chalcogenides in a simple, repeatable, single step process.20,21

Buried waveguides were fabricated in the 9 mm long substrate using ultrafast laser inscription (ULI).21 ULI is a convenient fabrication technique that offers three dimensional inscription capability: thus, it can be used in the fabrication of a number of complex optical devices.22 Central to ULI is the nonlinear absorption of sub-bandgap radiation inside a substrate, it can therefore be used to fabricate structures in a wide range of different materials. Our previous work on ULI in chalcogenides was based on single-scan inscription,20,21 where the waveguide cross-section exhibited a “teardrop” structure. Here we use a multi-scan inscription technique,23 allowing greater control over the waveguide cross-section and energy deposition. In Fig. 1(b), the facet image of an inscribed waveguide and the corresponding mode profile at 4.26 μm is shown. The waveguide cross-section is very different to those previously reported in chalcogenide glasses, due to lower energies required for multi-scan inscription, with no photo-darkening or regions of reduced refractive index in the material. The guided mode, shown in Fig. 1(c), is more confined and exhibits greater circular symmetry than previously reported waveguides inscribed in gallium lanthanum sulphide (GLS).21 The field of view for both the facet image and mode profile is 100 μm. The 1/e2 mode field diameter (MFD) was measured to be 45.5 μm in the axis orthogonal to the waveguide axis and inscription laser propagation direction and 44.6 μm in the axis parallel to the inscription laser propagation direction. The structures terminate approximately 55 μm from the end.
To generate the required 4.26 μm wavelength the signal and idler outputs of the optical parametric amplifier (Spectra-Physics OPA-800) were combined in a difference frequency generation (DFG) AgGaS2 crystal. The OPA was pumped by a regeneratively amplified Ti:Sapphire laser system and was operated with a pulse repetition rate of 1 kHz. With the DFG crystal module, this system has a tunable wavelength range of 1100–6500 nm. Since there is strong absorption at 4.26 μm in the atmosphere due to the presence of carbon dioxide it was necessary to encase the DFG and waveguide coupling optics in a positive pressure chamber. A continuous flow of oxygen-free nitrogen was pumped into the chamber in order to displace the atmospheric carbon dioxide. A schematic of the experimental set-up is shown in Fig. 1(a). This offers a potential route to tailor source spectra for maximum power delivery through the atmosphere. A focused beam of 22 μm MFD of the diffraction limited beam waist for the 20 mm focal length coupling lens with an input beam diameter of 5 mm. This was found to have a loss of 2.1 dB. The Fresnel loss from the glass—air interface is significant as GLS has a relatively high refractive index, which at 4260 nm was estimated to be 2.36. This was based upon extrapolation using the Sellmeier equation and a fit to index measurements reported in the literature. This resulted in a Fresnel loss of 0.78 dB and a total coupling loss of 2.88 dB. Using this loss residual signal and idler power is then blocked by a long-pass 3000 nm filter. The difference frequency output was collimated and passed through an MgF2 half-wave plate and a BaF2 wire grid polarizer allowing power and polarization control. The pulse width of the difference frequency pulse train was estimated to be 120 fs based upon the measured pulse width of the signal and idler output. Incident power measurements were made by a pyro-electric detector (Laser Probe Inc RkP-575) accessed by lowering a flip mirror, the beam then passed through a calcium fluoride window and onto the detector. Two 20 mm focal length calcium fluoride lenses were used to couple and then collect the light from the test waveguides. Both the calcium fluoride lenses were mounted on separate x, y, z translation stages (Elliot Scientific MDE122). The waveguide substrate was mounted on a four axis translation stage (Thorlabs MBT401). By changing the position of a second flip mirror, the waveguide output could either be directed onto a camera (FLIR SC7000) in order to record the guided mode profiles, or onto a monochromator (Zolix Omni λ 300) to record the output spectrum. The monochromator was used in conjunction with a PbSe detector (Thorlabs PDA20H) and a lock-in amplifier in order to measure the spectral power distribution.

Due to residual CO2 absorption outside of the purged chamber and in the monochromator the spectra are still affected by atmospheric absorption. This can be seen by observing the DFG spectrum as recorded by the monochromator. This spectrum is shown in Fig. 2 together with the theoretical input spectrum in the absence of CO2 absorption. However, with the chamber purged, the DFG signal is launched into the waveguide without any significant attenuation. The waveguide output spectrum was recorded with an incident pulse energy of 410 nJ. The actual launched energy can be estimated by considering the mode size mismatch between the 45 μm MFD of the waveguide and the 22 μm MFD of the diffraction limited beam waist for the 20 mm focal length coupling lens with an input beam diameter of 5 mm. This was found to have a loss of 2.1 dB. The Fresnel loss from the glass—air interface is significant as GLS has a relatively high refractive index, which at 4260 nm was estimated to be 2.36. This was based upon extrapolation using the Sellmeier equation and a fit to index measurements reported in the literature. This resulted in a Fresnel loss of 0.78 dB and a total coupling loss of 2.88 dB. Using this loss

FIG. 1. The concept of using self-phase modulation to reshape a pulse spectrum (SPM) around an absorption feature (Trans.) is shown in (a). The GLS waveguide facet is shown in (b) and corresponding mode image (c) at 4260 nm on the same scale. (d) Experimental arrangement for the coupling of mid infrared pulse train into GLS waveguide. The signal and idler outputs from an OPA source are focused inside a difference frequency generation (DFG) crystal. LPF, long pass filter; HWP, half wave plate; WGP, wire grid polarizer; FM1 and FM2 are flip mirrors.

FIG. 2. Input pulse spectrum centred on 4260 nm that has been shaped by atmospheric CO2 absorption (solid line). The fitted unmodified spectrum (broken line).
The high transmission of the GLS substrate used is marked and enables nonlinear spectral broadening to reshape the source spectrum and thereby enhance the transmission through the 3–5 µm atmospheric window. This will be of importance for the subsequent development of broadband sources for remote sensing and infrared countermeasures applications.

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