Designing silicon-core fiber tapers for efficient mid-IR supercontinuum generation

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We propose a taper design for a silicon-core fiber for the purpose of generating a supercontinuum (SC) from a 2.1µm pulsed fiber laser. The design is tailored to maximise the conversion efficiency (CE) to the 3-4µm region, which is important for environmental sensing as it includes several key greenhouse gas absorption lines.

There has been much interest in using a SC for this in recent years [1]. Some high power demonstrations [2, 3] have produced multi-milliwatt outputs in the 3-4µm range, but these required hundreds of milliwatts input.

There is a need for more compact, low-power and efficient solutions. Aluminium nitride photonic-chip waveguides have been shown to generate 0.3mW in the 3-4µm region with an 80mW input (at 100MHz) [4]. Although this is sufficient power for some applications, the system only offers a 0.4% CE. More recently a silicon nitride planar waveguide was used to transfer energy from a commercial 2.1µm femtosecond laser to the 3-4µm region [1]. In this demonstration, the long wavelength part of the spectrum was concentrated in a dispersive wave (DW) and so only covered ~500nm. Separate waveguides with different phase-matching conditions and increasingly higher coupled input powers were needed to push this DW from 3 to 4µm. To cover the entire region, it is estimated that an input of 40mW would be needed to generate ~1mW (CE of 2.5%).

Compared to these materials silicon has a higher nonlinearity and, despite multi-photon absorption, is highly efficient at transferring energy to different wavelengths with modest input powers. Moreover, silicon-core fibers can be tapered using established post-processing procedures [5], which can be used to control the phase-matching conditions to concentrate energy in a required wavelength range.

We have designed a silicon-core fiber taper that can take the input from a 2.1um fiber laser and efficiently transfer the energy to cover the entire 3-4µm range through self-phase-modulation, soliton fission and four-wave-mixing processes. The optimised taper is 6mm long and symmetrical, tapering down from ~3µm input to a 2.45µm waist before tapering up again. The larger input and output facets allow efficient coupling, and the waist diameter is chosen to maximise the nonlinearity while limiting short-wavelength generation.

We simulated SC generation using the generalised nonlinear Schrödinger equation including wavelength-dependent loss terms (linear, TPA and 3PA). From these simulations we estimate that ~0.8mW average power can be generated covering the entire 3-4µm region, with only 15mW input power, a CE of 5%. The output spectra are also very flat, with at least 0.05mW in each 100nm band. If the laser repetition rate can be scaled up from 19MHz to 100MHz, in line with [4], this would correspond to an input of ~80mW, and a target output of >4mW.

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[3] Heidt, A. M. et al., Opt. Express 21, 24281-24287 (2013).

[4] Hickstein, D. D. et al., Phys. Rev. App. 8, 014025 (2017).

[5] Ren, H. et al, Opt. Express 25, 24157-24163 (2017).