We report the demonstration of a mid-IR fiber gas laser using feedback in an optical cavity. The laser uses acetylene gas in high-performance silica hollow core fiber as the gain medium, and lases either continuous wave or synchronously pumped when pumped by telecoms-wavelength diode lasers. We have demonstrated lasing on a number of transitions in the spectral band 3.1 – 3.2 µm. The system could be extended to other selected molecular species to generate output in the spectral band up to 5 µm, and has excellent potential for power scaling. © 2015 Optical Society of America

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The mid-infrared represents a rapidly-evolving frontier for laser development. Quantum cascade lasers have steadily extended through this band but continuous-wave room-temperature emissions between 3 and 3.5 µm remain elusive [1]. The spectacular success of silica fiber lasers [2] cannot be extended much beyond 2.5 µm wavelength because silica becomes strongly absorbing at these longer wavelengths. Alternative glass systems such as chalcogenides have made great progress [3] but have drawbacks such as fiber strength and stability, nonlinearity and optical damage. Systems based on nonlinear conversion [4] are versatile but typically bulky and inefficient. We now demonstrate that a gas-filled silica-based hollow-core fiber laser enables both continuous-wave and synchronously-pumped mid-infrared (3.1 µm) lasing with sufficiently low threshold to be directly optically pumped by an unamplified (<20 mW) 1.5 µm diode laser, none of which has been demonstrated before in this spectral band. This system is convenient, robust, exhibits a low pump threshold, and has tremendous potential for scalability in footprint, power and wavelength in the mid-IR. Our interest is in creating a versatile laser technology for the 3-5 µm spectral band which is compact, rugged and scalable to high optical powers. Hollow core silica fibers combine the strength and durability of silica with record low attenuation in the 3-4 µm spectral band, where their attenuation can be ten thousand times less than that of bulk silica [5-7] and the equal of any conventional optical fibers [8, 9]. They also have a very high damage threshold [10, 11], very low group-velocity dispersion [12] and an optical nonlinearity that is many orders of magnitude less than that of competing fibers [13]. They thus have the potential to substantially outperform other fibers in the mid-IR. At wavelengths beyond 3 µm, softer glasses like chalcogenides are considered to have outstanding potential as hosts for rare earth elements. However, these glasses are hard to purify, not always stable in ambient conditions and difficult to draw into fibers. The silica-based hollow fibers used in our experiments offer a complementary approach to fiber lasers in the mid-IR, and are shown in Fig. 1. Further information is in supplementary information Table S1.

![Fig. 1.](https://example.com/fig1.jpg) Scanning electron micrographs of the two different forms of hollow fiber used in the experiment. Left - gain fiber with transmission at 1.53 µm and 3.1 µm wavelengths. Right - feedback fiber with lower loss at 3.1 µm.

Our work builds on recent research showing how molecular species such as acetylene and HCN can provide gain at mid-infrared wavelengths at low vapor pressure in a cavity when pumped with nanosecond pulses from an optical parametric converter [14], and how this system transfers into a hollow-core fiber in a single-pass amplified-spontaneous-emission configuration [15]. A system using acetylene as gain medium can be pumped using a stabilized, modulated, fiber amplified diode laser around 1530 nm [16]. In those experiments, although amplification of spontaneous emissions was enhanced by the waveguiding provided by the fiber, there was no cavity feedback and only pulsed single-pass operation was reported. Peak pump powers of tens of watts were required for appreciable conversion [15, 16] whilst continuous wave (CW) operation was not achieved. CW operation of an acetylene laser is made harder by the lack of a radiative transition from the lower lasing levels. The requirement for a non-radiative (collisional) de-excitation pathway affects the laser dynamics and limits the efficiency [17]. Recently, CW operation of a different molecular system...
at 1310 nm was reported [18]. A linear cavity incorporating a short (20 cm) straight hollow fiber placed within a gas cell containing molecular iodine was pumped with a tunable, single-frequency frequency-doubled Nd:VO<sub>4</sub> pump source. Very high fiber attenuation at the pump wavelength (> 40 dB/m) was overcome by using only a short fiber length and high gain from a molecular transition with a rapid de-excitation of the lower laser level.

Our feedback fiber (Figs. 1(b) and 3(a)) has one of the lowest attenuations reported for any optical fiber in this spectral band, enabling long optical cavities and hence low repetition rate pulsed lasing. The acetylene is pumped using a CW DFB diode laser tuned to one of the absorption lines around 1530 nm as shown in Fig. 3(b), which can be modulated and/or amplified using telecoms technology when required. For pulsed operation, the pump repetition rate is carefully adjusted (using a Stanford Digital Delay Generator DG645 to control the pump modulator) so that the circulating laser pulse is coincident in time with the 1.53 μm pump pulse. A dichroic mirror (high transmission at 1.53 μm, high reflection at 3.16 μm) is used to recombine the feedback with the pump before coupling into the gain fiber. Our use of feedback fiber as a part of a ring cavity configuration facilitates cavity alignment. A short feedback fiber (e.g. 3m) provides lowest loss for CW operation and a longer length (100m) allows pulsed operation at relatively low repetition rate. About 7% or 70% of the total power is coupled out of the cavity per round trip using an uncoated CaF<sub>2</sub> window or a coated custom-made optical component respectively as output coupler.

In operation, the pump was tuned to one of the acetylene P-branch absorption lines around 1530 nm. We used erbium-doped fiber amplifiers to increase the pump power to around 75 mW, and coupled around 80% of this into the gain fiber through the dichroic mirror. With a feedback fiber length of 3 m we then detected lasing at corresponding transitions around 3.1 μm, as illustrated in Fig. 4(a).

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**Fig. 2.** Experimental layout of the laser cavity.

Our system (Fig. 2) relies on the use of hollow core fiber in two ways. The first is to simultaneously confine the light (at both pump and laser wavelengths) and the molecular gain medium. The attenuation of the (empty) gain fiber at the pump wavelength of 1.53 μm is 0.11 dB/m and the attenuation around 3.1-3.2 μm, the laser wavelength band, is 0.10 dB/m. Our low-loss fiber enables the use of low gas pressure to provide a very high gain per pass. By using different gain fiber lengths, we found that 10m gives the best laser performance. The gain fiber is enclosed at each end in a small gas cell, providing optical access through a window. The cells and fiber were evacuated and then filled with a low pressure (typically, 0.3 mbar) of acetylene.

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**Fig. 3.** (a) Attenuation curve for the feedback fiber, showing an attenuation of 0.025 ± 0.005 dB/m over the laser wavelength band. Sharp features at 3.3 μm and beyond arise from small quantities of HCl gas present in the fiber core. The pink band indicates the uncertainty in the measurement of minimum attenuation. (b) The measured acetylene (¹⁴C₂H₂) P[9] absorption line measured in 10 m gain fiber with 0.3mbar pressure.

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**Fig. 4.** Continuous wave lasing of acetylene. (a) Measured optical spectra for different pump transitions (resolution 1 nm). (b) Selected acetylene molecular energy levels, showing the radiative transitions involved in lasing. Note that there is no radiative transition from the lower laser level to the ground state.
For CW pumping (Fig. 4(b)) we typically observed two lines arising from the \( \Delta J = \pm 1 \) transitions from the common upper level populated by the pump excitation. For each pump transition, the \( \Delta J = \pm 1 \) laser transitions share a common upper level [19] and so are in competition, and one might expect to observe just a single line above threshold. However, the gain for the above-threshold line is reduced as the population builds up in its lower lasing level, until it is exceeded by the gain provided to the competing line (with a lower lasing level which is still empty), allowing this second line to lase as well. Thus, broadly up to half of the pump photons can result in a laser photon for the highest-gain line, and up to half of the remainder can result in a photon on the second line. Highest output powers are obtained using 70% output coupling as in Fig. 5(a). Under CW pumping our cavity oscillated bi-directionally, with slope efficiency 6.7% (single output measured). No saturation of the output power was observed as we increased the pump power to the maximum (75 mW). To reduce the threshold we have used a lower output coupling of 7%. A reduced pump threshold of 16 mW then enables our cavity to lase when pumped directly by our unamplified pump laser, although with reduced efficiency. This configuration is ideal for use as a seed in a possible oscillator/amplifier configuration, with overall amplifier efficiency expected to be ~20% [16]. Fig. 5(b) shows the high beam quality of the laser output and the excellent stability of the laser over long time scales.

![Graph](image1)

**Fig. 5. (a)** Pump power/output power curve for pumping at 1530 nm on the P9 transition, showing a threshold of 34 mW and a slope efficiency of 6.7%. The output coupling used was 70%. The incident pump power is measured before coupling into fiber and the 3 \( \mu \)m output is measured after coupling out by the output coupler. The pump-coupling efficiency is 80%. Note that although the laser oscillates bidirectionally only one of the output is measured here. **(b)** Stability of laser output as a function of time, measured at 10 Hz over more than one hour. Note that apart from the standard stabilization of the pump laser diodes, there is no frequency locking of the pump or stabilization of the laser cavity. Inset shows the mode profile, measured using a two-dimensional scan across the output beam.

Replacing the feedback fiber with a longer fiber of 100 m length and modulating the pump into a train of 80 ns pulses causes a strong dependence of the 3.1 \( \mu \)m laser output on the repetition rate, as shown in Fig. 6. Maximum output power is recorded when the repetition rate is at the frequency of the ring cavity (2.6 MHz - synchronous pumping). When the pump repetition rate is changed, the lasing continues, although with reduced efficiency and stability. When the feedback is blocked no output can be detected. The laser power recovers around harmonic and sub-harmonic repetition rates. As the pump repetition rate is reduced (but without adjusting amplifier pumps), the pump pulse energy increases and less feedback is required to generate a detectable output, resulting in less sensitivity to the pump repetition rate as we approach the single-pass amplified spontaneous emission (ASE) regime. However, we are still unable to detect an output under any circumstances when the feedback is blocked because even at these lower repetition rates (0.1 MHz), the pump peak powers (5.8 W) and pulse energies (0.46 \mu J) are much lower than in previous single pass ASE experiments [16]. Increasing the repetition rate above the cavity frequency has a rapid decrease of the output indicating that the decay of the excited state is rapid even at low pulse energies. Spectrally, the output when synchronously pumped is dominated by a single strong line, with only the very weak detection of a second line. Using an average pump power of tens of milliwatts (peak power <100 mW at 2.6 MHz) we easily reach threshold for laser oscillation under pulsed pumping and our cavity oscillates with a slope efficiency of 8.8% as shown in Fig. 7. The threshold under synchronous pulsed pumping is not affected by reducing the output coupling indicating that the gain is saturated. Just as for continuous wave operation, the output was stable over many hours (see supplementary information Figure S1).

![Graph](image2)

**Fig. 6.** Pulsed lasing of acetylene. Measured output power as a function of pump repetition rate. The pump pulse duration is 80 ns. The pump amplifier current is kept fixed as the repetition rate is varied.

![Graph](image3)

**Fig. 7.** Pump power/output power curves for selected repetition rates. The slope efficiency at synchronous pumping is 8.8%, with just one spectral line lasing.
Emissions from the system when synchronously pumped take the form of a pulse train emitted at the round-trip repetition rate of the laser cavity, and correspond to copies of a single pulse circulating inside the cavity (see supplementary information Figure S2). Radio-frequency (RF) spectra of our laser are shown in Fig. 8(a) along with the optical spectrum of the laser (Fig. 8(b)) and the temporal profile of the pump and laser pulses (Fig 8(c)), for selected frequencies. When synchronously pumped (2.6 MHz) the RF spectra reproduce the noise characteristics of the modulated pump source: at other repetition rates they reveal the complex dynamics of asynchronous pumping. Further data is in supplementary information Table S2.

![Radio-frequency spectra](image)

**Fig. 8.** Shows radio frequency spectra (a), optical spectra (b) and time dependence (c) for the pump (blue) and the laser (red) at selected repetition rates spanning the peak performance in Fig 5. The optical spectra are normalized as a group to the peak spectral power at 2.6 MHz.

In conclusion, we report a diode-laser-pumped ring-cavity all-silica fiber gas laser with low threshold running stably around 3 μm wavelength either continuous wave, or pulsed with a repetition rate of 2.6 MHz. The laser is enabled by the remarkable properties of mid-IR hollow-core fiber formed from silica, and is pumped around 1530 nm wavelength. The system is scalable through the use of existing 15 μm laser technology using an oscillator/amplifier configuration, and could be extended to different wavelengths using other molecular gain systems up to 5 μm wavelength.

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See Supplement 1 for supporting content.

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Cavity-based Mid-IR Fiber Gas Laser Pumped by a Diode Laser

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