OSA / CLEO/QELS 2010

C_2H_2 Gas Laser Inside Hollow-Core Photonic Crystal Fiber Based on Population Inversion

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Abstract: Lasing from population inversion is demonstrated from gas contained in a hollow-core kagome structured photonic crystal fiber. Laser pulses in the mid-IR (3.1-3.2 µm) were generated by optically pumping at λ ~ 1.5 µm.

OCIS codes: (140.4130) Molecular gas lasers; (140.3510) Lasers, fiber; (060.5295) Photonic crystal fibers

1. Introduction

We demonstrate what we believe is the first optically pumped gas laser (OPGL) based on population inversion in a hollow core photonic crystal fiber (HC-PCF). The laser produces mid-IR (3.1-3.2 µm) lasing by optically pumping with 1.5 µm, nanosecond pulses. The laser has many of the advantages of optically pumped gas lasers (OPGLs), including high damage thresholds and the potential for coherent emission from mutually incoherent pump sources. Furthermore, OPGLs with molecular gases offer a variety of mid-IR wavelengths [1-2] specifically in the eye-safe wavelengths within the atmospheric transmission window. Creating an OPGL inside hollow fiber has the added advantage of confining the pump and laser light over long interaction lengths in a compact configuration. The feasibility of implementing molecular OPGLs inside a waveguide has been previously examined [3]. Many nonlinear optical phenomena have been studied in gas-filled hollow optical fibers, including the demonstration of a Raman laser [4]. Indeed, the kagome structured fiber employed there offers very broad guiding bandwidths, well suited for the present laser in which the pump and lasing wavelengths differ by nearly a factor of two.

2. Setup for the OPGL Inside HC-PCF

In this initial demonstration of a fiber OPGL, nanosecond pulses excite acetylene gas inside HC-PCF. This approach is motivated by an OPGL based on acetylene vapor inside a glass cell that demonstrated large optical gain near 3 µm [3]. The experiment is shown schematically in Fig. 1a.

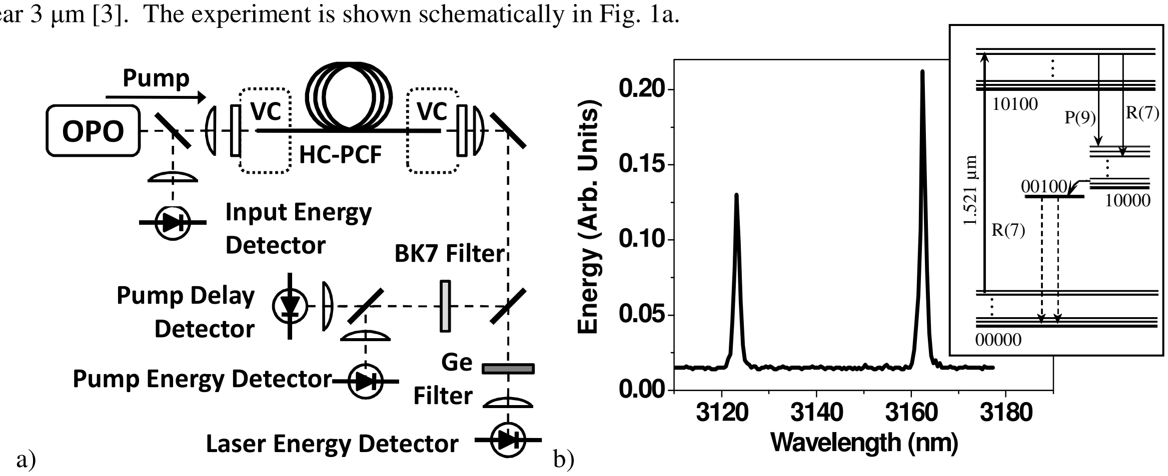

Fig. 1: a) Fiber OPGL setup. The acetylene filled HC-PCF is pumped using a nanosecond OPO. Incident pump energy, pump energy through the fiber, mid-IR laser pulse energy, and pump-to-laser pulse delay are monitored simultaneously. A germanium wafer transmits mid-IR laser pulses while attenuating pump pulses to below the noise level of the HgCdTe laser energy detector. A BK7 window is used to absorb mid-IR laser energy before the pump energy and timing detectors. b) Spectrum of laser output when C_2H_2 pressure was ~ 7 torr. Inset: Simplified energy level diagram of C_2H_2 showing the pump and two laser transitions.

An optical parametric oscillator (OPO) is used as the pulsed pump source, and its output pulses were typically 5 – 6 ns in duration with average pulse energies of ~ 5 mJ. The OPO was tuned to resonance with the $\nu_1 + \nu_3$ (R7) transition in $^{12}C_2H_2$, λ = 1521.06 nm. These pulses were directed into a vacuum chamber containing a single-cell kagome structured optical fiber of 1.65 m length, similar to that employed in Ref. [4]. This kagome fiber exhibits

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strong guiding in the near IR pump region (loss ~ 0.75 dB/m) and weak guiding behavior near 3 μm (~ 20 dB/m), as calculations suggest. The gain of the laser is sufficient that no cavity was required, in spite of the large loss in the lasing band.

3. Characterization of the Laser Output

Spectral output from the OPGL, shown in Fig. 1b for ~ 7 torr acetylene gas pressure, contains two peaks located near 3.12 μm and 3.16 μm respectively, corresponding to (R7) and (P9) rotational transitions between the $\nu_1 + \nu_3$ and ν_1 vibrational levels. The OPO pump, tuned to the (R7) rotational transition, moves population from the J = 7 rotational state of the ground state vibrational manifold to the J = 8 rotational state of the $\nu_1 + \nu_3$ vibrational manifold. This creates an immediate population inversion between the J = 8, $\nu_1 + \nu_3$ state and the essentially empty ν_1 vibrational state ($N_e/N_0 \sim \exp[-h\nu_1/kT] = 9 \times 10^{-8}$) resulting in the possibility of population transfer via the allowed (R7) and (P9) dipole transitions to the J = 7 and J = 9 rotational states. Pulsed laser output was observed for gas pressures between 0.5 torr and 20 torr.

Figure 2a shows the laser pulse energy output versus pump pulse energy for an acetylene pressure of 7 torr. This curve indicates the onset of saturation as the increasing pump pulse energy starts to saturate the absorption transition. At lower pressures, saturation is more pronounced. In Fig. 2b, the lasing output is plotted as a function of acetylene pressure for pump energies of 600 nJ coupled into the fiber (30 μJ incident on the fiber). The coupling efficiency was only ~ 2%, but values exceeding 50% into kagome fiber have been demonstrated. The temporal delay between the pump and laser pulses was also measured, and varied from less than 1 ns to greater than 10 ns. Shorter delays are observed when the pump power is further above threshold, when population inversion builds up more quickly. The lasing threshold, defined as the minimum pump pulse energy coupled into the fiber necessary to observe mid-IR laser output, is about 200 nJ, and varies with pressure. The slope efficiency of the laser, defined as the change in output energy divided by the change in pump energy coupled into the fiber, is a few percent.

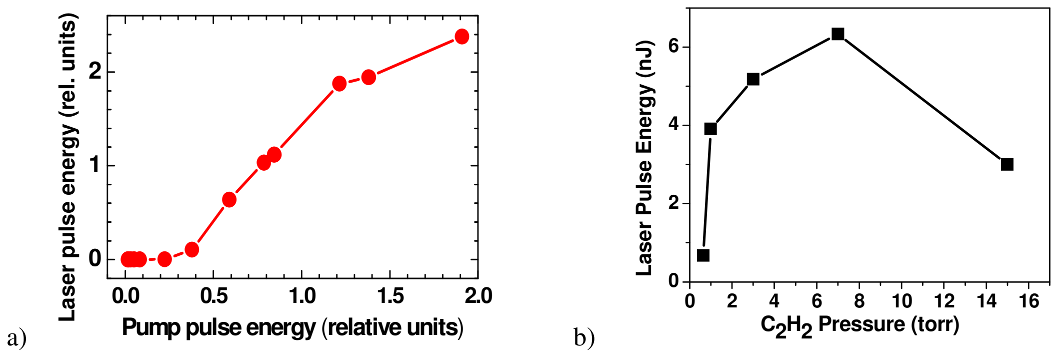

Fig. 2: a) Laser pulse output energy vs. pump pulse energy in relative units for 7 torr pressure acetylene gas. b) Mid-IR laser pulse energy vs. acetylene pressure when pumped at 30 μJ incident input pulse energy for several acetylene pressures inside the HC-PCF.

Reduction of the kagome fiber loses at the laser wavelength should substantially increase the slope efficiency and decrease the threshold. Furthermore, the addition of an optical cavity or increased kagome fiber length may also improve laser performance. Modeling efforts are ongoing. While this first demonstration uses a pulsed pump, the gas-filled fiber laser is particularly attractive for pumping with continuous wave laser sources.

4. Acknowledgements

This work was supported by the Air Force Office of Scientific Research (FA9550-08-1-0344), Army Research Office (W911NF-08-C-0106 and W911NF-08-1-0332), National Science Foundation (PHY-0722622), Joint Technology Office (W911NF-05-1-0507), Engineering and Physical Sciences Research Council, and Precision Photonics Corp.

5. References

[1] J. E. McCord, H. C. Miller, G. Hager, A. I. Lampson, and P. G. Crowell, "Experimental investigation of an optically pumped mid-infrared carbon monoxide laser," *IEEE J of Quantum Electronics,* vol. 35, pp. 1602-1612, 1999.

[2] A. Ratanavis, N. Campbell, A. V. V. Nampoothiri, and W. Rudolph, "Performance and Spectral Tuning of Optically Overtone Pumped Molecular Lasers", *IEEE J of Quantum Electronics,* vol. 45, pp. 488 2009.

[3] A.V.V. Nampoothiri, A Ratanavis, N. Campbell, and W. Rudolph, "Molecular C_2H_2 and HCN lasers pumped by an optical parametric oscillator in the 1.5-μm band", submitted to Optics Express, 2009.

[4] F. Couny, F. Benabid, P. J. Roberts, P. S. Light, and M. G. Raymer "Generation and Photonic Guidance of Multi-Octave Optical-Frequency Combs"*Science* vol. 318, pp. 1118, 2007.