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Lasers Using Low Loss Hollow Optical Fibres in the Mid-Infrared

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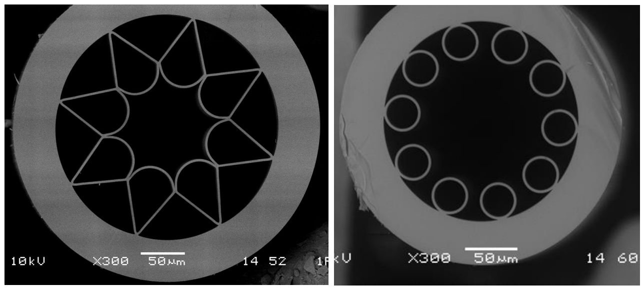
Abstract—**A new generation of very low loss hollow fibers (~30 dB/km at 3 µm) in the mid-IR has opened up the possibilities for fiber gas lasers and laser beam delivery in this challenging spectral region.**

Keywords—optical fiber; mid-infrared; gas laser; fiber laser

I. INTRODUCTION

Hollow optical fibers confining light in a hollow core by a photonic bandgap formed in an intricate periodic cladding were first developed 15 years ago [1]. Such fibers promised a revolution in the way one can think about optical fiber materials. No longer was one limited to solid materials forming a fiber core, but gases became possible, and one could imagine that one also might not be limited in the wavelength range of operation by the stringent material transparency requirements of solid optical fibers, or limited in power level by damage or nonlinearity in the fiber. Since then much of this promise has been realized in high energy pulse transmission [2,3] and nonlinear interactions in gases [4]. Unfortunately, whilst excellent performance has been demonstrated and great physical insights have been gained, such fibers remain difficult to fabricate and so are uncommon and costly. Many of the advantages of hollow-core photonic bandgap fibers can however be achieved in simpler structures using anti-resonant features to confine light in a hollow core. This process of simplification has culminated in the development over the last couple of years of hollow fibers with the functional cladding structure reduced to the boundary of the hollow core, formed by a thin glass wall whose thickness and shape defines the fiber properties [5,6,7].

In a relatively short space of time these new fiber designs have revolutionized the way in which one can think of using hollow optical fibers. The simplicity of the structure (Fig. 1) and broad transmission bands makes fabrication much less challenging for any particular application. Furthermore these hollow core silica fibers have been shown to have extremely low attenuation, particularly in the mid-infrared (of the order of 30 dB/km at 3 µm [6,8]) where one would expect a silica fiber to be highly attenuating (bulk attenuation 50 dB/m). Here we consider two applications taking advantage of this new generation of long, low-loss, large core, mid-infrared fibers – fiber gas lasers with electrical and optical pumping. These applications illustrate the properties of the fiber which are also useful for high power laser beam delivery, gas sensing, nonlinear Raman wavelength conversion and other uses in the mid-IR.



(a) (b)

Fig. 1. Hollow-core fibres designed for mid-IR guidance. Fibre (b) has less suceptability to bend loss. The fabrication and guidance of these fibres are considered in [6] and [7].

II. GAS DISCHARGE LASERS

Electrically-pumped lasers using DC glow discharges were amongst the first lasers to be demonstrated and were among the early commercial laser successes. For the neutral noble gas lasers (notably He:Ne, but also neutral Xe, Ar and Kr) it was shown that the inversion and gain is enhanced at higher pressure in smaller diameter discharge tubes [9]. Unfortunately there has always been a limit to exploring this effect as diffraction of a free-space laser beam becomes significant for diameters of the order of 1 mm. Grazing incidence reflection in a thick walled capillary can provide some measure of guidance, but with high loss and extreme sensitivity to bending. Nevertheless lasers were demonstrated using gas discharges in specially straightened short capillaries [10,11]. A hollow core optical fiber immediately overcomes the guidance limitation, but can present difficulties with achieving the electrical discharge – breakdown voltages rise for small tube diameters, which is compounded by the fact that the optimum gas pressure required for lasers increases for small tubes and the breakdown voltage rises further for higher pressures. Many of the first hollow-core optical fibers, particularly those with photonic bandgaps, have very small cores, a few times the wavelength. The new generation of fibers using anti-resonant guidance (of the types shown in Fig. 1) have much larger cores, typically of

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the order of 30 λ. Furthermore there are particularly strong laser transitions in the mid-infrared (He:Ne at 3.39 μm, Xe at 3.51 μm), where the relatively long wavelength also means the fibers are physically larger. Overall these two effects mean that the fiber core diameter is large enough for the glow discharge to be initiated and maintained relatively easily, whilst the structure is still far smaller than previous attempts and can also be long and flexible. Using a fiber with a structure like Fig. 1(b) we have initiated gas discharges up to 1 m in length with discharge voltages of the order of 15 kV in He:Xe mixtures at 12 mbar [12]. The fiber core diameter was ~120 μm with an attenuation <0.2 dB/m at 3.5 μm. Fig. 2 shows the super-linear dependence of single-pass output with fiber length, demonstrating gain.

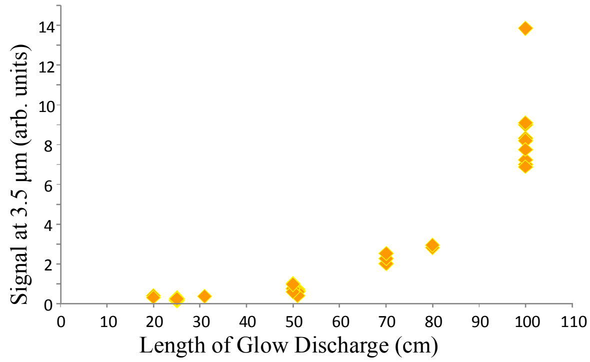

Fig. 2. Single pass output signalat 3.5 μm for a 5:1 mixture of He:Xe at 12 mbar pressure for 0.25 mA discharge current.

III. Optically-Pumped Gas Lasers

Optically pumped gas lasers have gained interest recently, partly because the precisely controlled pump lasers required to address the narrow pump transitions of gas lasers can now be remarkably compact. By placing the gas in an optical fiber one may increase the length and hence gain and potentially output power of the laser. Many of the useful transitions are in the mid-IR [13,14], where the new fibers excel. Also this application benefits from the large core diameter as this reduces collisional broadening of the atomic transitions at low pressure, and the low attenuation allows for a long length to achieve pump absorption in the low pressure gas. We have demonstrated high single-pass gain and high conversion efficiency at 3.16 μm in a hollow core fiber filled with acetylene [15] pumped with a fiber amplified telecommunications tunable DFB laser at 1530.37 nm. The stability achieved by standard current and temperature control in the DFB laser is sufficient to remain on resonance with the Doppler-broadened acetylene transitions without need for any active locking. Indeed the absolute accuracy of the diodes, even several years after factory calibration, is within a few hundred megahertz of the molecular transitions before fine tuning. The pump laser was modulated into nanosecond pulses before amplification, as the acetylene transitions are self-terminating and the lower laser level must be depopulated by molecular collisions or wall collisions. Fig. 3 shows the output spectrum. The single pass conversion efficiency is high; for a 10.5 m fiber length at 0.7 mbar the threshold pump energy was 50 nJ, and the conversion efficiency >20% at 2 μJ pump energy.

IV. Conclusion

Hollow core silica fibers using anti-resonant structures are a key new technology enabling exciting new openings in fiber lasers. We have demonstrated strong ASE and gain in electrically- and optically-pumped gases in the mid-IR based on these fibers and many more opportunities arise including nonlinear conversion in gases and high power beam delivery.

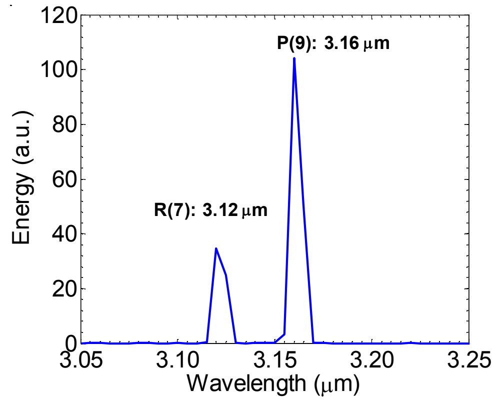

Fig. 3. Measured output optical spectrum of $^{12}C_2H_2$ at 0.7 mbar pressure, 10.5 m length, and 4.2 μJ incident pump energy.

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