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Holey fibers: fundamentals and applications

D.J. Richardson, W. Belardi, K. Furusawa, J.H.V Price, A.Malinowski and T.M. Monro

Optoelectronics Research Centre, Southampton University, SO17 1BJ, UK
Tel: +44 23 8059 4524, Fax: +44 23 8059 3142,
E-mail: djr@orc.soton.ac.uk

Abstract

We explain the physical operating principles of holey fibers, review some of their unique optical properties and go on to describe a number of ultrafast applications of this rapidly developing technology.

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Holey fiber technology promises the development of fibers with a wide range of unique optical properties suitable for use in ultrafast optics applications. As a first example, consider the fiber shown in Fig.1a. In this fiber the high index difference between glass and air results in strong optical confinement of light down to dimensions of order the wavelength resulting in a very high value of effective nonlinearity per unit length [1]. Moreover, the manner in which light at different wavelengths 'experiences' the high index regions of the fiber results in unusual waveguide dispersion properties that are simply not possible using conventional single mode fibers. The fiber of Fig.1a for example has a predicted zero dispersion wavelength of ~800nm, and zero dispersion wavelengths as short as 550nm have been reported in the literature [2]. Such a combination of exotic dispersive and nonlinear properties at wavelengths readily generated by conventional femtosecond pulse sources (e.g. Ti:Sapphire lasers) promise the development of a host of useful fiber based devices. These include sources based on soliton effects (e.g. pulse compressors [3], wavelength tunable sources based on the soliton self frequency shift (SSFS) [4]), and white light sources based on supercontinuum generation [5]. Indeed, this last form of source is already finding widespread application in metrology where the ability to generate coherent light with frequencies spanning more than two octaves is proving a major development. Such fibres are also of interest for telecommunications applications. For example, we recently demonstrated a 2R data regeneration device based on self phase modulation and offset spectral filtering using just 3.3m of HF with an effective mode area of 2.8μm^2 at 1.55μm [6], and a Raman amplifier providing gains of up to 43dB[7].

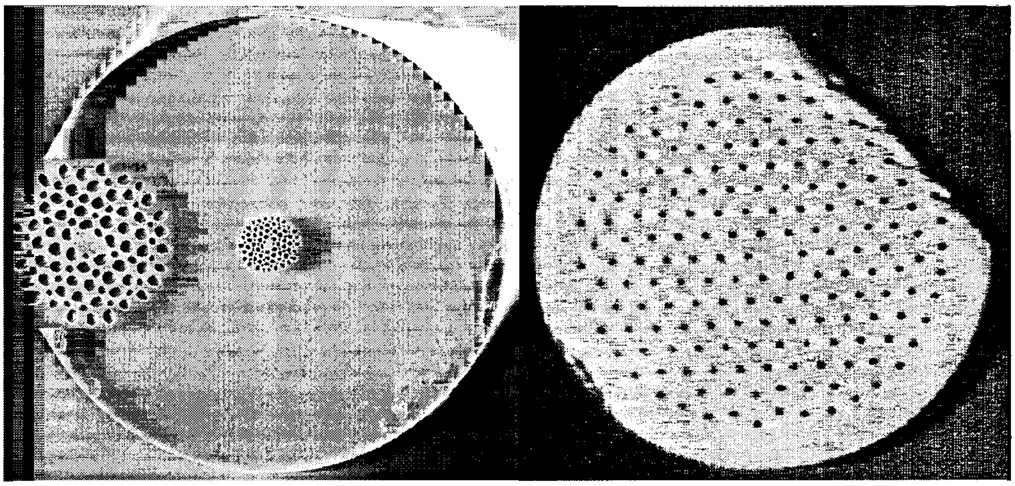

Fig.1. Some typical generic holey fiber types: (a) a small core holey fiber (~1.5μm in diameter) which provides tight mode confinement, high optical nonlinearity and anomalous dispersion at visible wavelengths (inset is a magnified SEM image of the core), (b) A large mode area holey fiber (core diameter ~15μm) for high optical power delivery.

At the other mode size extreme holey fibers, such as the fiber shown in Fig.1b, with small holes and large hole spacings offer extremely large mode areas (and correspondingly low optical nonlinearities) [8]. Large mode area fibers have potential applications in high power optical delivery including laser welding and machining, and high power fiber lasers and amplifiers. Although conventional fibers can exhibit similar characteristics at any given wavelength, HFs have a distinct advantage for broadband and short wavelength applications since they can be single-moded over a large wavelength range. The largest mode size that can be tolerated in practice is determined by macroscopic bending losses, and recent work demonstrates that HFs can possess comparable bend losses at 1.55μm to similarly sized conventional fibers [9].

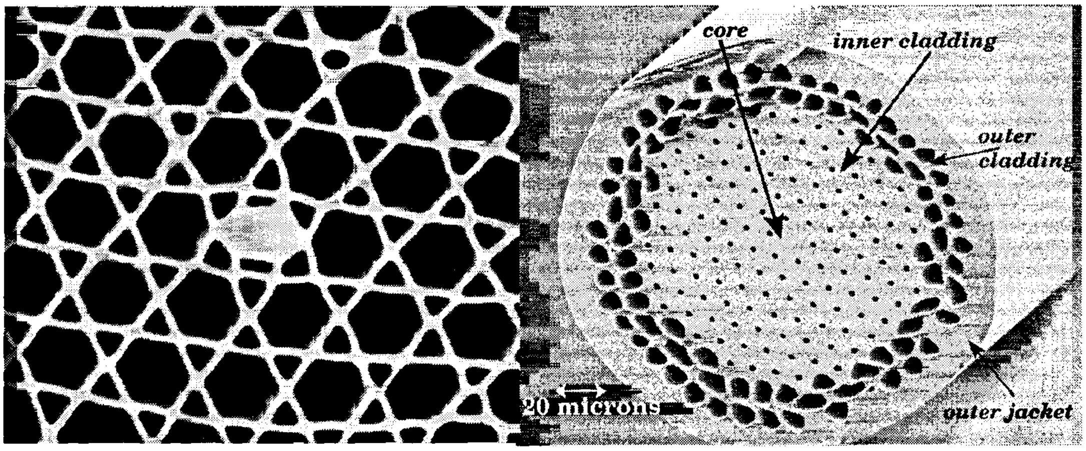

Fig.2 Rare earth doped holey fibers: (a) a small, (1.5μm by 2.5μm), elliptical core, Yb-doped holey fiber with anomalous dispersion for λ>800nm and, (b) an air clad, Yb-doped, large mode area holey fiber suitable for cladding pumped fiber laser and amplifier applications.

Holey fiber technology is also of relevance to the production of doped fibers, as required for example in fiber laser and amplifier systems. For example, using the high nonlinearity Ytterbium-doped HF shown in Fig.2a we demonstrated a low threshold, tunable, mode-locked soliton laser [10]. Using the same fiber we have developed an all-fiber femtosecond soliton source continuously tunable over the wavelength range 1.06-1.33μm based on the combined effects of pulse amplification and the soliton self frequency shift [11], which again relies upon the fiber having anomalous dispersion over this wavelength range. Holey fiber technology also lends itself readily to the cladding pumping technique as shown in Fig.2b. In this fiber the small inner holes around the solid Yb doped 'defect' region define a large mode area single mode waveguide, whilst the larger air holes that surround this inner-cladding region define a high NA (NA~0.4-0.5) multimode waveguide for 980/915nm pump radiation. Using this all-glass structure we achieved laser action in the range 1030-1100nm on a single transverse mode with a power conversion efficiency of 80% [12]. The high NA inner cladding allows for higher pump intensities, shorter device lengths and increased operating bandwidth than for conventional polymer coated high power cladding pumped fiber devices, and this is likely to result in significant benefits in the design and performance of ultrafast fiber laser and amplifier systems.

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