[illegible]
[illegible]
Baltimore

2555

Holey Fiber Based Nonlinear Optical Devices for Telecommunications

Ju Han Lee, Walter Belardi, Tanya M. Monro, and David J. Richardson,

The wavelength-scale features in holey fibers lead to novel properties including endlessly single-mode guidance, high optical nonlinearity. The state-of-the-art HF technology for nonlinear optical signal processing devices is reviewed from a viewpoint of possible applications for telecommunications.

The rapid development of holey fibre (HF) technology in recent years has resulted in widespread interest in the use of such technology for a variety of fiber-optic communication devices and applications [1]. HF, also referred to as microstructured fiber and photonic crystal fiber, possesses a solid core surrounded by a cladding region that is defined by a fine array of air holes that extend along the full fiber length (see Fig.1). HF's are typically made of a single material, usually pure silica, and guide light through a modified form of total internal reflection since volume average refractive index in the core region of the fiber is greater than that of the surrounding microstructured cladding. Note that the hole diameter (d) and pitch (Λ=hole to hole spacing) which are the critical design parameters used to specify the structure of an HF are typically on the scale of the wavelength of light [2].

The large index contrast between glass and air and the small structure dimensions combine to make the effective cladding index a strong function of wavelength. This unusual wavelength dependence leads to a host of unique and tailorable optical properties. One striking property is that fibers with a low air fill fraction ($d/\Lambda < 0.4$) can be single-moded regardless of operating wavelength [3]. This property is particularly significant for broadband or short wavelength applications. Arguably, the most exciting possibility afforded by HF technology is the opportunity to develop fibers with a very high optical nonlinearity per unit length [4,5]. Tailoring the scale of the cladding features allows the effective fundamental mode area of a holey fiber at 1.55μm to be extremely small ($A_{eff} \sim 2\ \mu m^2$) [2]. Thus, One of the most promising applications of HF's is in the development of nonlinear optical signal processing devices for fiber-optic communication systems. HF's can have much higher nonlinearity per unit length than conventional fibers, and devices based on such fibers can thus be much shorter in length, and/or operate at lower power levels.

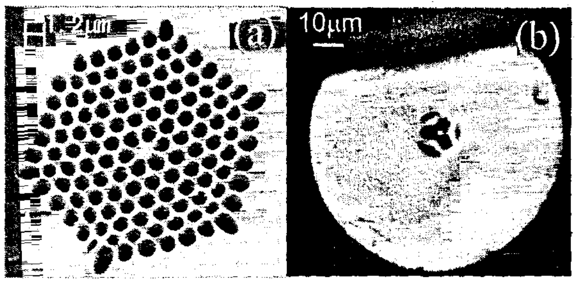

Fig.1. SEM's of highly nonlinear HF's fabricated at ORC: (a) normal dispersion HF, and (b) ultra-high nonlinearity HF in Schott SF57 glass.

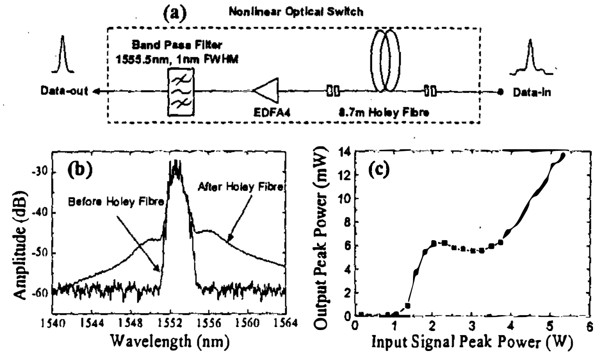

Fig.2. (a) The schematic of the nonlinear optical thresholder, (b) spectra of pulse before and after HF, (c) power transmitted through the full system including the offset narrowband filter.

For example, we demonstrated a 2R data regeneration device based on a HF with an effective mode area of just $2.8\mu m^2$ and a nonlinearity $\gamma=31 W^{-1}km^{-1}$ at 1.55μm [6]. The 2R regenerative operation was obtained by combining self-phase modulation and offset narrowband spectral filtering. Similar devices based on conventional fibers are typically of order 1 km in length whereas in our earliest experiments just 3.3m of HF was needed for an operating power of 15W. We went on to use an 8.7m long variant of this switch to provide an optical thresholding function within an optical code division multiple access (OCDMA) system [7]. A schematic of the thresholder is shown in Fig.2a. In Fig.2b we show the spectrum of 2.5ps soliton pulses both prior and after propagation through the highly nonlinear HF. As can be seen from Fig.2b new spectral components are generated at both red and blue shifted frequencies relative to the incoming spectrum. In Fig.2c we show the pulse power transmitted through a 1.0nm narrowband filter which was offset spectrally by + 2.5nm relative from the central wavelength of the incident pulses as a function of incident pulse peak power. The S-shaped characteristic is suitable for optical thresholding applications. We used such a switch prior to our OCDMA receiver to eliminate the low-level pedestal components arising from the matched filtering of coded bits and obtained a significant improvement in the overall system performance.

Such fibers also offer reduced length/power requirements for nonlinear devices based on other nonlinear effects such as the Brillouin and Raman effects [8,9]. For example, we demonstrated a ~75m long, fiber laser pumped Raman amplifier [8]. A schematic of the experimental set up is shown in Fig.3a.

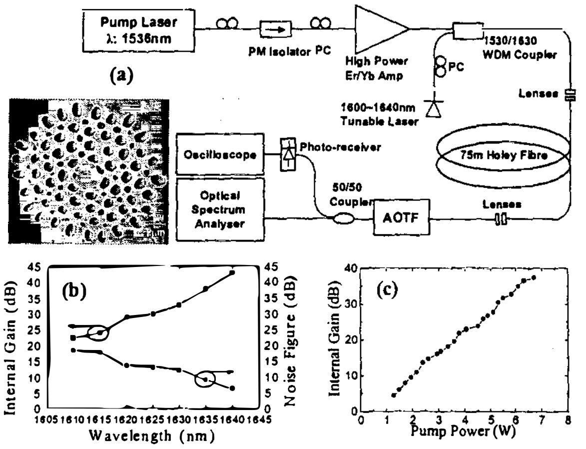

Fig.3. (a) Schematic of our HF amplifier (AOTF- acousto-optic tunable filter); Inset: SEM image of the HF used. (b) Wavelength dependence of gain, (c) gain efficiency curve at a wavelength of 1635nm.

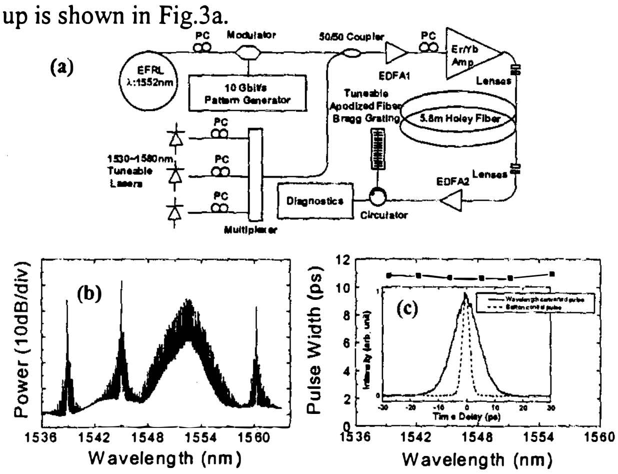

Fig.4. (a) Experimental setup for a HF based wavelength converter, (b) measured optical spectra of probe and control signals, and (c) pulsewidth as a function of probe beam wavelength

The amplifier was pumped using a pulsed fiber laser operating at a wavelength of 1536nm and provided high gains of up to 43dB in the L^+ - communications band (see Fig.3b) for pulse peak powers of order 7 W (see Fig.3c). Subsequently, we constructed a Brillouin laser based on a Fabry-Perot resonator which incorporated a 73.5 m long holey fiber, a lens-coupled high-reflectivity cavity mirror and a 96 % output coupler defined by the Fresnel reflection from the cleaved fiber facet at the pump launch end of the cavity. The laser had a Brillouin shifted output power of 110 mW and a slope efficiency of 70% [9].

Wavelength conversion is another important function required within current high-capacity WDM systems. We recently demonstrated that HF technology can be applied to multiple wavelength conversion over a ~15nm bandwidth at a data rate of 10 Gbit/s using a combination of XPM in a short length of HF, and narrowband spectral filtering [10]. The experimental setup is shown in Fig.4a. XPM between the control signal and the CW beams results in chirping of the CW laser beam where these beams overlap temporally within the fiber. This frequency chirping can then be converted to a frequency converted signal by passing the signal through a narrowband filter which serves to eliminate the residual unchirped CW signal as well as to select one of the two XPM-induced side bands. The pulsewidths of the converted pulses were observed to be almost constant at ~11 ps over a wavelength range of ~15nm (see Fig.4c).

An alternative, and more flexible wavelength conversion approach, is based on four-wave mixing (FWM). FWM is particularly attractive for wavelength conversion due to its relative transparency to both bit-rate and modulation format. Highly efficient, broadband wavelength conversion based on FWM in optical fibre requires high nonlinearity, small dispersion, a low dispersion slope, and a short fibre length to reduce the phase mismatch between the interacting waves [11,12,13]. In addition, a high stimulated Brillouin scattering (SBS) threshold is required to suppress SBS induced pump power loss in order to permit higher conversion efficiency [14]. Thus, highly nonlinear HF with a high SBS threshold could be a powerful nonlinear medium for FWM based wavelength conversion. We have demonstrated tuneable FWM based conversion using a highly nonlinear HF with a high SBS threshold [15]. The experimental setup is shown in Fig. 5a. In order to obtain a highly nonlinear HF with a high SBS threshold we used an HF with structural nonuniformity along its length [9]. The SBS threshold of the 15m HF was measured to be ~120mW, around two times higher than would be expected for a silica fibre with a uniform cross-sectional profile. Fig. 5c shows the measured conversion efficiency. A maximum conversion efficiency of −16 dB was achieved over a 3dB bandwidth of ~10nm. Error-free wavelength conversion performance with a ~2dB power penalty relative to that of the back-to-back input signal was readily achieved.

Furthermore, HF can be applied to all-optical time-division multiplexing (TDM) data demultiplexing which is one of key nonlinear signal processing functions for high-speed OTDM systems. Recently, L. Oxenlowe et al. demonstrated a high-speed OTDM demultiplexer based on a 50m long HF [16]. Error-free operation at 160Gbit/s data rate was achieved with the nonlinear optical loop mirror based demultiplexer.

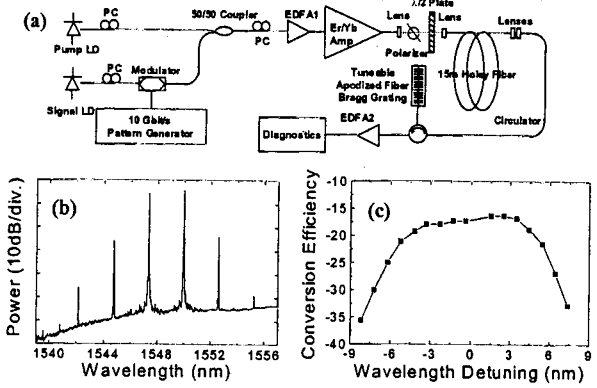

Fig.5. (a) Experimental setup for FWM based CW wavelength conversion using a nonuniform HF, (b) output optical spectrum from the HF, and (c) the measured conversion efficiency.

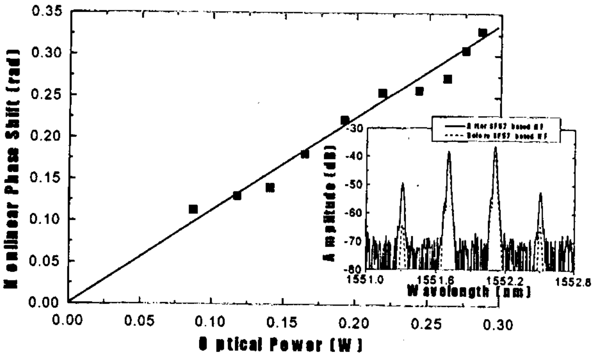

Fig.6. Nonlinear phase shift versus launched power for the SF57 fiber shown in Fig.1b which yields an estimated value of the effective nonlinearity parameter $\gamma=550\ W^{-1}km^{-1}$; Inset: Spectral sidebands of high power dual frequency beat signal.

Note that these previously described device demonstrations have used silica based holey fibers but that further significant increases in fiber nonlinearity should be achievable using fibers made of other glasses. The first results in this direction have now been obtained and a SF57 lead glass HF with $\gamma=550\ W^{-1}\cdot km^{-1}$, about 500 times more nonlinear than conventional SMF28 fiber demonstrated [17]. Note that this particular fiber was produced from a preform manufactured using extrusion and highlights the fact that use of glasses with lower softening temperatures (~600 °C for SF57 versus ~2000 °C for silica) opens the possibility of new HF fabrication approaches. A picture of this small core SF57 fiber is shown in Fig. 2b, along with a plot of the measured nonlinear phase shift as a function of power in Fig.6.

In conclusion, recent progress of HF based nonlinear optical devices has been reviewed in terms of possible application for telecommunication systems. HF technology has advanced now to the point that km-lengths of robust coated fiber can be produced with losses as low as 0.58 dB/km [18]. Such fibers with a broad range of unique and useful optical properties could have the potential to enable a variety of practical optical devices, nonlinear or linear for a wide range of applications areas, both within telecommunications and beyond.

* The authors would like to thank Mr. Z. Yusoff, Dr, M. Ibsen, and Dr. K. Furusawa for their help.

References

[1] D.J. Richardson et al. "Holey fibers for nonlinear fiber devices, " *Proc. OAA'2002*, Invited paper OMD1 (2002).
[2] T. M. Monro et al., "Holey optical fibers: an efficient modal model," *J. Lightwave Technol.*, **17**, pp.1093-1102 (1999).
[3] T. A. Birks et al., "Endlessly single-mode photonic crystal fiber, " *Optics Lett.*, **22**, pp.96-963 (1997).
[4] N.G.R.Broderick et al. "Nonlinearity in holey optical fibers: measurement and future opportunities", *Optics Lett.*, **24**, pp.1395-1397, (1999)
[5] K.P. Hansen et al., "Highly nonlinear photonic crystal fiber with zreo dispersion at 1550nm", *Proc OFC'2002*, Postdeadline FA9-1, (2002).
[6] P. Petropoulos et al., "2R-regenerative all-optical switch based on a highly nonlinear holey fiber, " *Optics. Lett.*, **26**, pp.16-18 (2001).
[7] J.H. Lee et al., "A holey fiber based nonlinear thresholding device for optical CDMA receiver performance enhancement," *IEEE Photon. Technol. Lett.*, **14**, pp.876-878 (2002).
[8] J.H. Lee et al., "A holey fiber Raman amplifier and all-optical modulator," *Proc. ECOC'2001*, Postdeadline PD.A.1.1, (2001).
[9] J.H. Lee et al., "Investigation of Brillouin effects in small core holey optical fiber: lasing and scattering, " *Optics Lett.*, **27**, pp.927-929, (2002).
[10] J. H. Lee et al., "Holey fiber based WDM wavelength converter incorporating an apodized fiber Bragg grating filter, " *Proc. CLEO'2002*, Postdeadline (2002).
[11] J. E. Sharping et al., "Four-wave mixing in microstructure fiber," *Optics Lett.*, **26**, pp.1048-1050 (2001).
[12] K. Inoue et al., "Wavelength conversion experiment using fiber four-wave mixing," *IEEE Photon. Technol. Lett.*, **4**, pp.69-72 (1992).
[13] O. Aso et al., "Broadband four-wave mixing generation in short optical fibre, " *Electron. Lett.*, **36**, p.709-711 (2000).
[14] J. Hansryd et al., "Increase of the SBS threshold in a short highly nonlinear fiber by applying a temperature distribution," *J. Lightwave Technol.*, **19**, pp.1691-1697 (2001).
[15] W. Belardi et al., "A 10 Gbit/s tuneable wavelength converter based on four-wave mixing in highly nonlinear holey fibre," *Proc. ECOC'2002*, Postdeadline PD1-2 (2002).
[16] L. K. Oxenløwe et al., "A photonic crystal fibre used as a 160 to 10 Gb/s demultiplexer," *Proc. OECC'2002*, Postdeadline PD1-4 (2002).
[17] T.M. Monro et al., " High nonlinearity extruded single mode holey optical fibers", *Proc OFC 2002*, Postdeadline FA1-1, (2002).
[18] L. Farr et al., "Low loss photonic crystal fibre", *Proc. ECOC'2002*, Postdeadline PD1-3 (2002).