Demonstration of amplified data transmission at 2 µm in a low-loss wide bandwidth hollow core photonic bandgap fiber

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Abstract: The first demonstration of a hollow core photonic bandgap fiber (HC-PBGF) suitable for high-rate data transmission in the 2 µm waveband is presented. The fiber has a record low loss for this wavelength region (4.5 dB/km at 1980 nm) and a >150 nm wide surface-mode-free transmission window at the center of the bandgap. Detailed analysis of the optical modes and their propagation along the fiber, carried out using a time-of-flight technique in conjunction with spatially and spectrally resolved (S^2) imaging, provides clear evidence that the HC-PBGF can be operated as quasi-single mode even though it supports up to four mode groups. Through the use of a custom built Thulium doped fiber amplifier with gain bandwidth closely matched to the fiber's low loss window, error-free 8 Gbit/s transmission in an optically amplified data channel at 2008 nm over 290 m of 19 cell HC-PBGF is reported.

OCIS codes: (060.2280) Fiber design and fabrication; (060.5295) Photonic crystal fibers; (060.4005) Fiber optics amplifiers and oscillators; (060.2300) Fiber measurements.

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1. Introduction

Since the advent and commercialization of the Erbium doped fiber amplifier and dispersion shifted fibers in the late 1980s, research and development in long-haul telecoms optical fibers has focused on the 1.55 μm wavelength region. Over the past decade, R&D efforts have been almost exclusively focused on optimizing the transmitters and receivers and on designing ever more advanced modulation formats. In contrast, comparatively little progress has been reported on the transmission fiber itself. More recently, however, the quest for radical solutions to increase transmission capacity per fiber, decrease fiber loss and nonlinearity and reduce signal latency has stimulated interest in novel and more exotic fiber types [1, 2]. High-risk, high-payoff fiber solutions are being actively pursued, which may eventually justify a shift away from the traditional operating wavelengths. Hollow core-photonic bandgap fibers (HC-PBGFs) hold great promise as a transmission medium due to their ultra-low nonlinearity and lower latency as compared to conventional solid fibers. These properties stem from the unique ability of HC-PBGFs to guide light in a hollow core, with minimal overlap (as low as 0.1%) between the optical field and the silica glass structure. Still a maturing technology, HC-PBGFs cannot yet rival the loss levels of standard silica single mode fiber [3]. However, steady and substantial progress has been made recently in understanding and engineering the transmission properties of these complex optical fibers. For instance, an eight-fold improvement in the transmission bandwidth of low loss (3.5 dB/km) HC-PBGFs has recently been reported [4]. This result was achieved by combining a 19-cell core design, offering low scattering loss [5], with a thin wall surround [6], enabling surface mode-free operation over a 160 nm wide window at the center of the optical bandgap. Through a similar fiber design principle, a wide bandwidth low loss 37 cell HC-PBGF was also recently demonstrated [7]. The ability to obtain a wide, low-loss transmission region is a key step to enable dense wavelength division multiplexing (DWDM) in these fibers, where a well-tempered dispersion profile [8] is also of crucial importance. Furthermore, whilst low-loss HC-PBGFs are inherently multi-moded, it was shown that, through a combination of optimized fiber structure (to suppress surface modes) and selective input and output coupling [4], these fibers can be operated as quasi-single mode to a level that meets the challenging requirements for error-free data transmission. Recently, 1.5 Tbit/s transmission (37x40 Gbit/s on-off keyed DWDM channels on a 100-GHz ITU grid) was demonstrated over 250 m of a HC-PBGF [9], further improved to 30.7 Tbit/s (96x320 Gb/s) dual-polarization (DP)-32QAM using coherently-detected, polarization-multiplexed transmission [10]. More recently, a record capacity of 73.7 Gbit/s was demonstrated through a combination of DWDM and mode-division multiplexing (MDM) using the three lowest order modes of a 37 cell HC-PBGF [11].

Loss reduction is however the key issue which will eventually determine whether HC-PBGFs are capable of outperforming conventional single mode fibers (SMFs). Whilst there is substantial evidence that the limiting loss factor of HC-PBGFs is scattering from roughness at the air/silica interface, the intrinsic limit has not yet been determined conclusively. Thus, it is still unclear whether losses below the conventional SMF levels, or indeed below the current state of the art of 1.7 dB/km [5, 12] are feasible in HC-PBGFs. In any case, both theoretical predictions [12] and recent experimental data [13] demonstrate that the minimum loss is shifted to longer wavelengths around 2 μm in HC-PBGFs as a consequence of the infrared 'multiphonon' absorption being effectively decreased by the substantially reduced modal overlap with the glass. Conveniently, this operating window coincides with that of Thulium doped fiber amplifiers (TDFAs), which offer the widest gain band (about 28 THz wide window from ~1750 to ~2050 nm) amongst all rare earth doped fiber amplifiers (e.g. C + L band of Erbium amplifiers is only ~12 THz), providing further potential advantage to expand the overall fiber capacity. It is also to be noted that optical components operating at 2 μm are becoming more and more readily commercially available due to relevance to other application sectors (e.g. high power fiber lasers, industrial processing, sensing and defense). Whilst data transmission experiments have been reported in the past [14, 15], the significant advantage offered by HC-PBGFs over solid fibers opens up new opportunities to re-investigate this relatively unexplored wavelength region.

In this paper we present the characterization of the modal properties of a wide bandwidth (152 nm), record-low loss (4.5 dB/km) HC-PBGF for operation at 2 μm. We then assess its data transmission capabilities using a combination of state-of-the-art commercially available 2 μm transmitter and receiver components and a custom built TDFA. We report the first error-free transmission of an optically amplified data channel at 8 Gbit/s at 2008 nm over a 290 m length of HC-PBGF [16]. We believe that this ground-breaking result represents a fundamental step towards assessing this radically novel fiber solution for next generation transmission systems.

2. Fiber fabrication and characterization

The HC-PBGF utilized in the present study had a 19-cell core structure and was fabricated from a stacked preform using a two-step drawing procedure. A Scanning Electron Micrograph (SEM) image of the fiber is shown in Fig. 1(b). The cladding is composed of 6½ rings of holes with an average spacing of ~5.5 μm and average relative hole size of ~0.96-0.965. The hollow core, 36 μm in diameter, has a thin surround and an expansion ratio relative to the cladding engineered to minimize the number of surface modes and thus to obtain low-loss guidance over a broad wavelength interval [4]. The sample used in this particular experiment was about 300m long, however it is possible to obtain about 2 km of HC-PBGF per single draw using our current fabrication process and we are actively investigating strategies to substantially further increase the yield per draw.

The fiber's spectral attenuation, measured via a careful cutback from 300 m to 5 m using a white light source and a long wavelength optical spectrum analyzer (OSA), is shown in Fig. 1(a). This measurement procedure was chosen to preserve the fiber sample but this measurement procedure leads to a probable overestimate of the loss due to the residual presence of higher order modes. The minimum loss value of 4.5 dB/km at 1980 nm is the lowest reported to date for a HC-PBGF operating in the 2 μm wavelength region. The 3 dB transmission window of the HC-PBGF is approximately 152 nm wide, which is well matched to the TDFA gain bandwidth, see Fig. 1(a).

Transmission spectra with higher wavelength resolution, Fig. 1(c), collected using a Tm amplified spontaneous emission (ASE) source and input/output coupling via SMF pigtails, reveal the presence of gas lines due to the (20012)-(00001) absorption band of CO_2 in the wavelength interval 2000-2020 nm, superimposed to a smaller background modulation, likely due to modal interference. The lines are 2-4 dB in strength, have a 80-100 pm 3 dB width with 0.5-0.8 nm separation. As no particular precaution was taken in order to prevent ingress of atmospheric gas into the fiber during fabrication, we believe that CO_2 in our fibers is due to atmospheric content and previous measurements support this hypothesis [17]. While we have previously demonstrated that these undesirable spectral features can be eliminated by flowing dry gas through the fiber [17] or through an improved fabrication process (e.g. by evacuating and purging the fiber preform to remove any atmospheric CO_2 prior to fiber drawing), here we demonstrate that error-free transmission can be achieved even at these wavelengths by tuning the signal to fit between absorption lines.

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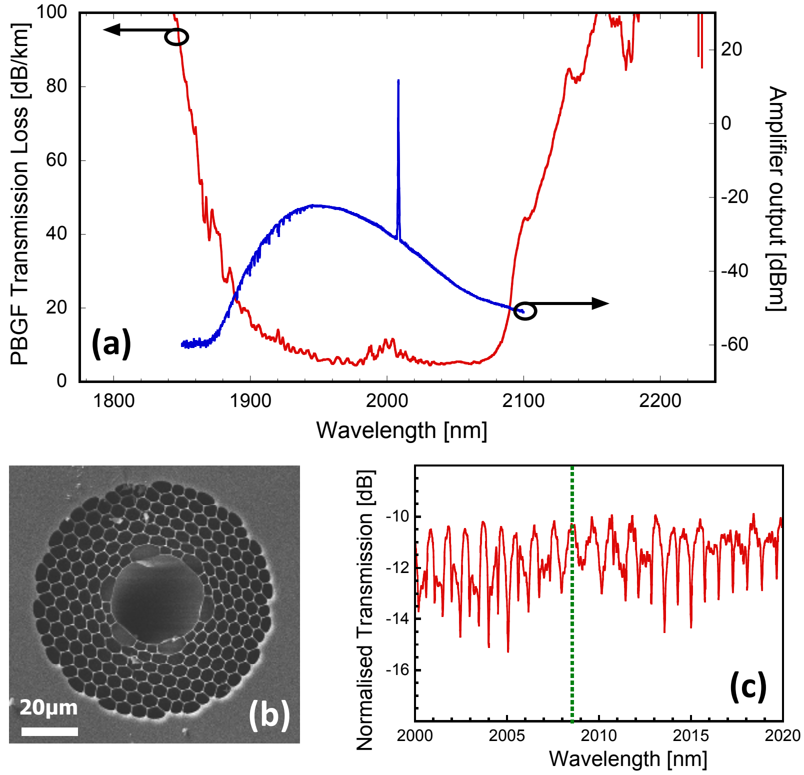

Fig. 1. (a) HC-PBGF transmission loss (300 m to 5 m cutback, 2 nm resolution) superimposed on the TDFA output to illustrate the location of the signal channel at 2008 nm and extent of ASE emission as an indicator of the amplifier bandwidth. (b) SEM image of the fiber. (c) High resolution (~50 pm) transmission of 290 m of HC-PBGF at 2000-2020 nm collected using a Tm:ASE source and SMF input and output coupling fibers and normalized against input intensity. Also shown the signal wavelength (green line) tuned off the CO_2 absorption lines.

The modal properties of the HC-PBGF were investigated by using an S^2 imaging technique [18]. Our setup was based on a Tm:ASE source, a scanning single-mode fiber probe and a long wavelength OSA (Yokogawa AQ6375). An 8 nm wide interval centered at 2008 nm was sampled at the maximum resolution of the OSA (50 pm). Light from the Tm:ASE source was launched into the HC-PBGF was via a standard SMF-28 fiber. The results obtained for a 10.7 m long HC-PBGF sample (loosely coiled at ~300 mm diameter) are shown in Fig. 2. In addition to the fundamental mode, three further mode groups were identified, i.e. the LP_{11}, LP_{21} and LP_{02}. Under optimized launch conditions, we obtained very low multi-path interference (MPI) values (<-40 dB) for all higher order modes. A slightly higher level of background as compared to measurements carried out on similar HC-PBGFs at 1.5 µm [4] was noted, which is probably due to the higher noise level of the long wavelength OSA. Despite this, the lack of a flat "plateau" feature between the peaks provides a clear indication of low cross-coupling between the modes.

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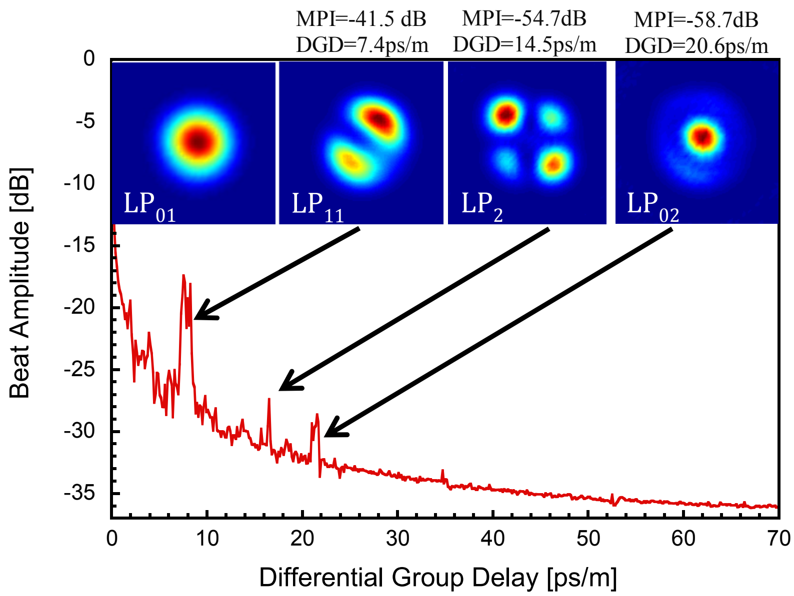

Fig. 2. Modal analysis of the HC-PBGF carried out over a 10.7 m fiber length via S^2 imaging at 2008 nm, showing the reconstructed modal profiles and values of differential group delay relative to the fundamental mode.

In order to investigate potential intermodal cross-coupling over a longer fiber length and to assess the potential of single-mode operation we used a time-of-flight (ToF) technique [4]. For this, a mode-locked fiber laser operating at 1940 nm (1 ps pulses at 25 MHz repetition rate, from AdValue Photonics), an 8 GHz bandwidth extended InGaAs PIN photodetector (Electro-Optics Technology, ET-5010F) and a fast sampling oscilloscope were used. Both ends of the HC-PBGF were butt-coupled to SMF-28, providing selective input and output coupling into the fundamental LP_{01} mode. Figure 3 shows the results for a 290 m long HC-PBGF sample under optimum coupling conditions to the LP_{01} mode. The photodiode exhibited some ringing in the 0–1.5 ns range, which has been corrected for in Fig. 3, but results in a slightly elevated residual noise floor. The expected peak positions corresponding to the higher order modes, determined from differential group delay (DGD) values obtained from the S^2 measurement, are also shown in Fig. 3.

Despite the large mismatch between the LP_{01} mode of the HC-PBGF and that of the launch/collection fibers, we achieved a remarkable 33 dB suppression of the LP_{11} mode with any contributions of higher order modes falling below the noise floor of 37 dB (Fig. 3). The peak marked ‘X’ in the figure, which appears with about 1 ns delay and 28 dB below the fundamental mode, has no counterpart in the measured S^2 spectrum and thus has not yet been clearly attributed (we speculate that it could be due to a discrete coupling point between LP_{01} and LP_{11} along the fiber length).

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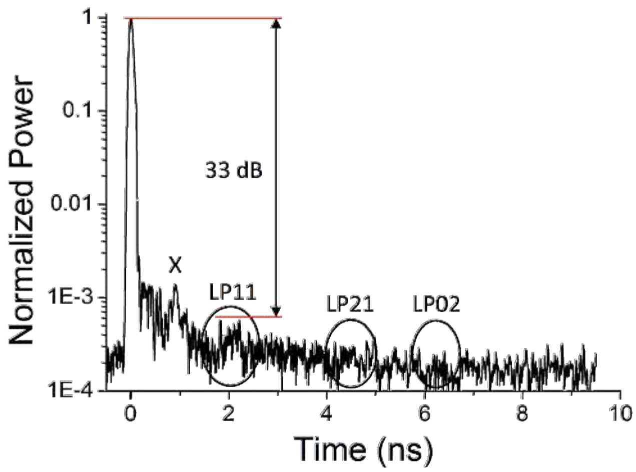

Fig. 3. Time-of-flight measurement at 1940 nm over a 290 m long HC-PBGF. The expected position of higher order modes (obtained from DGD values measured via S^2) is also shown, highlighting excellent suppression through optimized input and output coupling.

3. Experimental set-up

A schematic of the full transmission set-up used in this work, highlighting the various components, is shown in Fig. 4. The single mode diode laser used for the transmission experiments was a discrete-mode continuous-wave laser based on a multiple quantum well ridge waveguide InGaAs structure on InP substrate [19]. The device was purpose-developed for this experiment but is now commercially available [20]. The output intensity vs. bias current, showing a threshold current (I_{th}) of ~16 mA and slope efficiency (SE) of 0.06 mW/mA, is represented in Fig. 5(a). The laser provided 6 dBm maximum output power at ~2008 nm with side mode suppression ratio of ~45 dB, as shown in Fig. 5(b). The laser wavelength was temperature tuned to ensure that it lay between two adjacent CO_2 absorption lines (as shown in Fig. 1(c)). The laser diode, packaged in a butterfly module which contained a TEC and thermistor, had a very high frequency stability (~100 MHz or ~1.3 pm maximum excursion measured over a 60 min period). Furthermore, the CO_2 absorption lines are very insensitive to environmental effects and the shift with temperature is extremely small (<<1 MHz/K) and thus is totally negligible for this study.

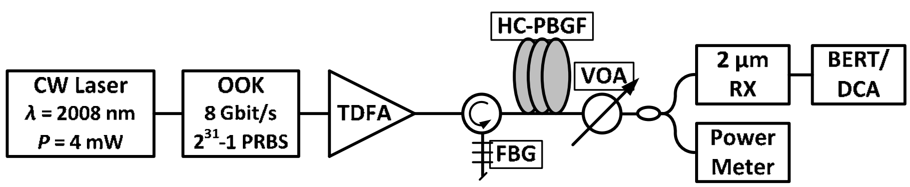

Fig. 4. Schematic of the full transmission setup. Signal from laser diode is modulated via an external LiNbO modulator through on-off keying (OOK), passed through a Thulium fiber amplifier (TDFA), a fiber Bragg grating (FBG) filter to remove the ASE noise, launched into the 290 m of HC-PBGF, passed through a variable optical attenuator (VOA) and finally detected by a fast photodetector and bit error rate tester and digital communications analyzer (BERT/DCA)

The laser was intensity modulated with a 2^{31}-1 pseudorandom bit sequence (PRBS) using an external lithium niobate Mach-Zehnder modulator (Photline Technologies). Its nominal electro-optical bandwidth was 1-2 GHz; however in this particular experiment it was operating at 8 Gbit/s, which was the maximum repetition rate for which we could achieve

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error-free back-to-back operation. Two examples of optical eye diagrams at 1Gbit/s and 8 Gbit/s, measured using an InGaAs high speed PIN detector (this was the same device used for the ToF measurements) are shown in Fig. 6. The corresponding electrical eye diagrams are also reported for completeness. The modulator had ~60 ps rise time and over 25 dB extinction ratio with an overall loss of 8 dB.

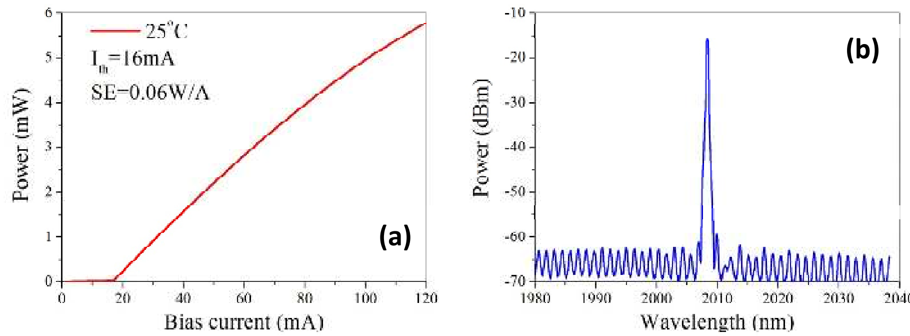

Fig. 5. (a) Discrete mode CW laser power as a function of bias current showing the threshold current and slope efficiency (SE). (b) Optical emission spectrum at a bias current of 100 mA.

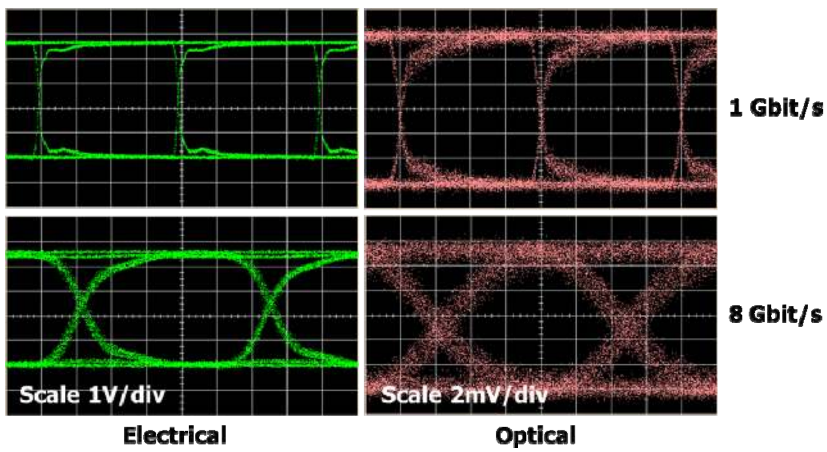

Fig. 6. Performance of the optical modulator at 1 Gbit/s (top) and 8 Gbit/s (bottom): electrical driving signal (left) and optical modulated signal (right).

The generated non-return-to-zero on-off keyed (NRZ-OOK) signal was then amplified using a TDFA pumped at 1565 nm, a schematic of which is shown in Fig. 7. The TDFA [21] was built with a commercially available Tm^{3+}-doped fiber (OFS TmDF200) having a mode field diameter of ~6.2 µm at 2000 nm and a core absorption of ~20 dB/m at 1565 nm. The amplifier consisted of two sections of TDF. Firstly, a 12 m long length of TDF was forward core pumped by an in-house built fiber Bragg grating (FBG)-stabilized single mode Er^{3+}/Yb^{3+} co-doped fiber laser operating at 1565 nm. The 1565 nm pump wavelength was chosen rather than the 790 nm pumping scheme commonly used for high power TDF devices since this offers lower noise performance around 2000 nm [22]. The pump and signal wavelengths were combined using a 1570/2000 nm WDM coupler. Isolators were placed both at the input and output ends to prevent parasitic lasing. A second, 4 m long length of TDF was inserted between the input isolator and the WDM coupler. This additional piece of fiber was indirectly pumped by the backward-travelling amplified spontaneous emission (ASE) generated from the directly pumped 12 m TDF section and provided additional signal gain at the longer

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wavelength end of the Tm gain window, i.e. around 2000 nm. This pumping scheme is similar to that used in L-band EDFA designs [23].

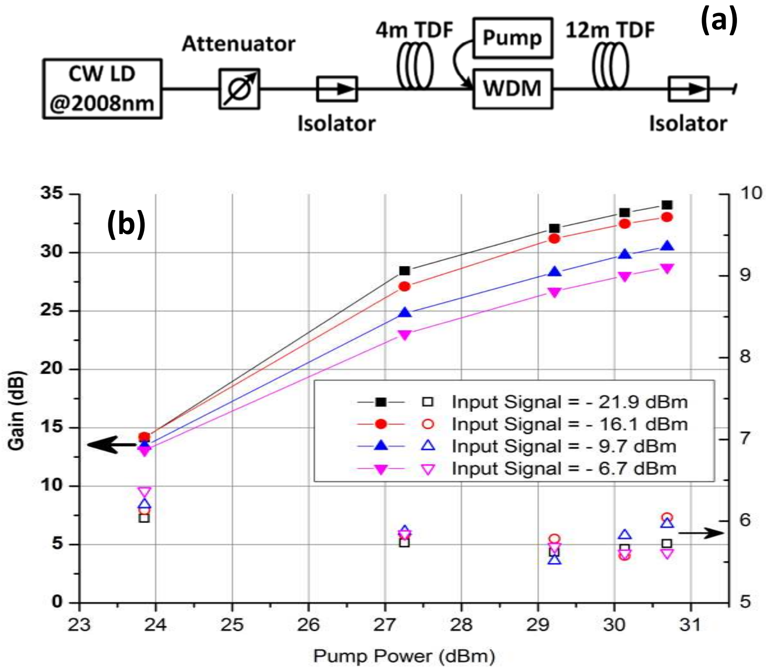

Fig. 7. (a) Detailed schematic of the Tm doped fiber amplifier shown as a single block in Fig. 4. (b) Gain and noise figure of the TDFA operating at the signal wavelength of 2008 nm.

Figure 7(b) shows the TDFA gain and external NF as a function of pump power for different input signal powers. The amplifier is capable of providing a maximum gain of 34 dB for a signal input power of −21.9 dBm and a saturated output power of 22 dBm. Its NF decreases with increasing pump power or amplifier gain. A minimum NF of ~6 dB was measured for input powers ranging from −21.9 dBm to −6.7 dBm when the pump power exceeds ~27 dBm. The internal NF was measured to be less than 5 dB. A more detailed analysis and a discussion of the method used for the amplifier characterization can be found elsewhere [20]. The TDFA output was then filtered by a FBG with 2 nm reflection bandwidth centered around the signal wavelength, to suppress amplified spontaneous emission from the amplifier and increase the out of band signal suppression to >50 dB. The signal was then butt-coupled into and out of the HC-PBGF via SMF-28 pigtails with particular care taken to ensure reliable excitation of the fundamental mode as previously discussed. The transmitted signal was detected using the extended InGaAs high-speed detector. The total insertion loss through the pigtailed HC-PBGF was ~10 dB, mostly attributed to coupling losses due to the large modal mismatch between the HC-PBGF (~22 µm MFD) and the SMF-28. It should be noted that the use of an amplifier was not strictly required to perform the transmission test given the relatively low insertion loss of the HC-PBGF span. Rather, we used it here to demonstrate the feasibility of using this technology with the much longer (and less lossy) fiber spans we anticipate will become available in the near future. Also note that a direct diode-pumped version of the amplifier (rather than fiber-laser-pumped used for the present study) has become available [24], which represents a significant advancement in terms of compactness, robustness, controllability and power consumption.

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4. Transmission results

The performance of the transmission system both before and after transmission through the fiber was assessed in terms of eye diagrams and bit error ratio (BER). Figure 8 shows eye diagrams and BER curves with and without the HC-PBGF (labeled as HC-PBGF-290m and back-to-back, respectively). Good open eyes were observed at the output of the fiber with negligible degradation compared to the back-to-back performance, which confirmed that modal cross talk effects were negligible over the measured length. This was also quantified by the corresponding BER measurements. The power penalty was negligible at a BER of 10^{-3} and increased up to 1.2 dB at 10^{-9}. No BER floor was observed when measuring BERs down to the 10^{-11} level. It should be noted that the choice of data rate was solely limited by the bandwidth of the amplitude modulator and photoreceiver used in the experiment. With 20 GHz bandwidth photoreceivers and a first generation of WDM components now beginning to appear on the market it appears entirely feasible that substantially higher data rates and overall capacities could soon be achieved in wide transmission bandwidth HC-PBGFs.

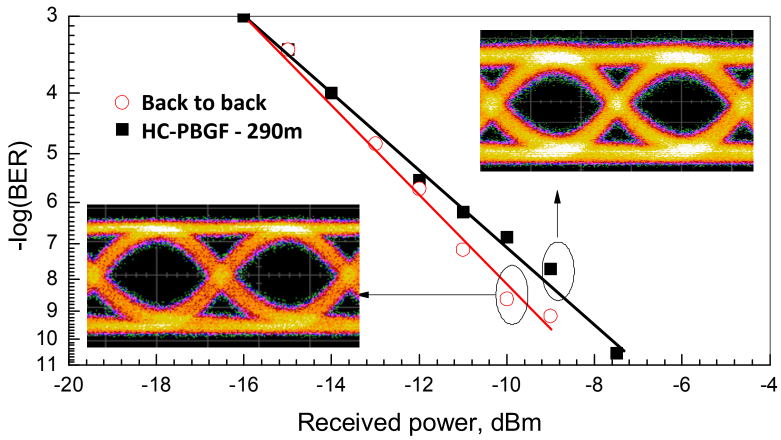

Fig. 8. Amplified transmission experiments at 2008 nm over 290 m of HC-PBGF: BER characteristics at 8 Gbit/s and eye diagrams corresponding to back-to-back and transmission over the fiber.

5. Conclusions

We have presented the first demonstration of a low loss, wide bandwidth 19-cell HC-PBGF suitable for high data rate single mode transmission at 2 μm and highlighted the suitability of TDFA technology for broadband amplification in the anticipated minimum loss window for this emerging fiber type. Our fiber exhibits a transmission loss of 4.5 dB/km (the lowest value reported to date for a HC-PBGF operating at 2 μm), a wide bandwidth (152 nm) and very low modal crosstalk (<-33 dB SMF-to-SMF) between fundamental and higher order modes, enabling quasi-single mode operation over a 290 m length. Error-free transmission of an 8 Gbit/s amplified channel at 2008 nm was demonstrated with only minor power penalty. Whilst a few challenges still remain to be addressed, and in particular the loss reduction benefit has yet to be demonstrated, this work result provides the first demonstration of the technological viability of using HC-PBGFs operating at wavelengths around 2 μm (in conjunction with TDFAs) as a possible basis for future generation high-performance optical communication systems. Future work will need to address the pressing challenge of achieving low loss over longer HC-PBGF lengths, and the more practical issues of interconnection, elimination of gas absorption and the investigation of long term reliability of these fibres.

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