# 81 Gb/s WDM Transmission at 2μm over 1.15 km of Low-Loss Hollow Core Photonic Bandgap Fiber

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**Abstract** *This paper presents WDM transmission at 2μm over 1.15km of HC-PBGF with wavelength channels selected to span a 36.3nm waveband. A total capacity of 81Gbit/s was achieved using 4×12.5Gbit/s NRZ-OOK external modulation and 4×7.7Gbit/s 4-ASK Fast-OFDM direct modulation signals.*

## Introduction

Ongoing research efforts are developing optical systems that can deliver higher capacities to accommodate the ever increasing growth of high bandwidth Internet traffic. With such growth, it is inevitable that the fundamental propagation characteristics of standard single mode fiber (SMF) will ultimately limit the total per-fiber capacity[1]. Operators will therefore be faced with future decisions as to how best to upgrade the infrastructure for certain high-capacity links making the development of new fiber types with the potential for higher capacity of acute interest. Recently, we introduced the concept of shifting the transmission band from the conventional C-band to 2μm[2], in order to exploit the potential low loss that Hollow Core Photonic Bandgap Fibers (HC-PBGF) may provide, in addition to their lower nonlinearity and latency as compared to standard SMF[3]. At this waveband, one can also exploit optical amplification from Tm-doped fiber amplifiers (TDFA) which operate over a wide bandwidth extending from ~ 1.80μm to 2.05μm[4], as well as the increasing availability of telecom-grade optical components, such as 2μm lasers[5], modulators and photodetectors[6]. We previously showed that modulation formats often used nowadays at ~1.55μm can also be implemented at 2μm, either via direct laser modulation, or external modulation, and demonstrated the first WDM transmission experiment over 290m of specially designed HC-PBGF[2].

In this paper we show for the first time 81 Gbit/s WDM transmission at 2μm over 1.15km low-loss HC-PBGF, nearly 4x further than previously reported. This was achieved by using a newer generation of laser sources, a higher speed photodetector, and by improving the fiber fabrication; we recently reported record loss reduction to 2.5dB/km at ~2.1μm[7]. The 81Gbit/s total capacity was achieved by directly modulating four lasers with 4-ASK Fast-OFDM[8], each at 7.7Gbit/s (excluding 7% FEC overheads), and externally modulating four lasers with NRZ-OOK at 12.5Gbit/s, spanning a total bandwidth of 36.3nm.

## Experimental Setup

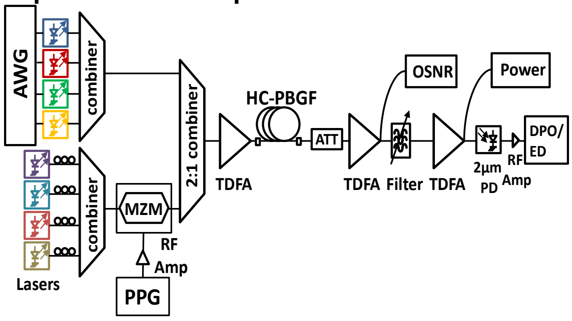


**Fig. 1:** Experimental Setup

Fig.1 shows the experimental setup for the WDM system. The transmitter consisted of four directly modulated (1967.6, 1977.8, 1986.9, and 1992.5nm) and another four externally modulated (1995.7, 1998.4, 2001.9, and 2003.9nm) channels. The lasers used were based on highly strained $In_{0.74}Ga_{0.26}As$ multiple quantum well, ridge waveguide laser diode structures grown on InP substrates and designed for single mode operation at these wavelengths[5]. The four lasers used for direct modulation presented 3-dB RF bandwidths up to 5GHz, with 4-ASK Fast-OFDM the modulation format of choice, in this case, maximizing the spectral efficiency.

Two independent 4-ASK Fast-OFDM signals generated by a 5GS/s Arbitrary Waveform Generator (AWG), together with their delayed versions, were used to modulate the four directly modulated lasers. Each 4-ASK Fast-OFDM used 128 discrete cosine transform point size, among which 106 subcarriers were used for data modulation. Double side-band 4-ASK Fast-OFDM signal provides a spectral efficiency of 2 bit/s/Hz, so the total data rate per channel was 8.3Gbit/s, or 7.7Gbit/s taking into account overheads for FEC at 7%. Each Fast-OFDM frame consisted of one start-of-frame symbol for synchronization[8] and 100 payload symbols.

The remaining 4 channels were externally modulated using a $LiNbO_3$-based Mach-Zehnder Modulator (MZM) with a $V_\pi$ of 9.5V, driven by a $2^{31}$-1 pseudo random bit sequence (PRBS) at 12.5Gbit/s, from a pulse pattern generator (PPG). The overall data rate of these channels was limited by the combined 3-dB RF bandwidth of the MZM and photo-detector (PD) of about 12GHz.

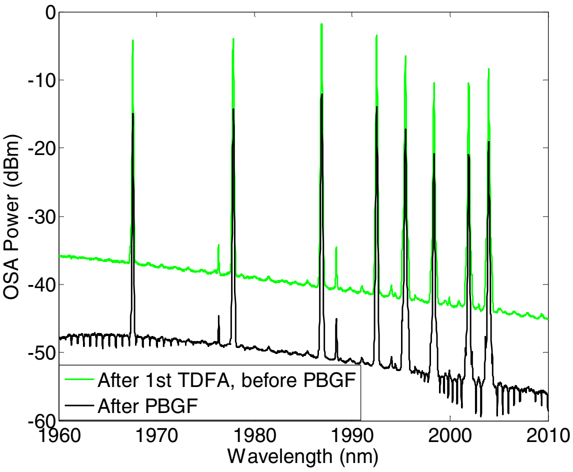


**Fig. 2:** Spectrum before and after HC-PBGF transmission. OSA resolution: 0.05nm.

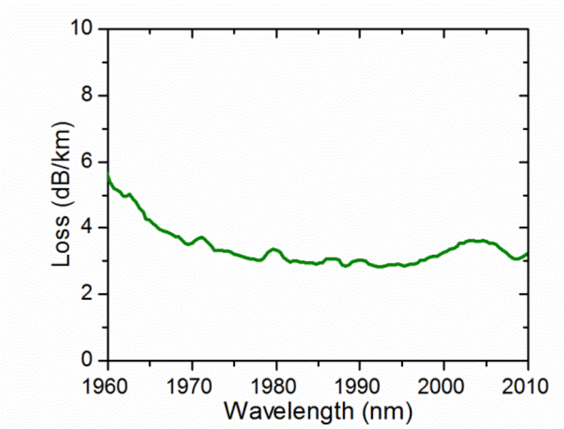


**Fig. 3:** Loss of the HC-PBGF measured with the cut-back technique. Peaks within the loss spectrum are due to $CO_2$ and water vapour absorption.

Prior to transmission, a TDFA[4] was used in order to both compensate for the transmitter losses and pre-compensate for the fiber losses. Fig. 2 shows the spectrum of all 8 lasers after the 1st TDFA (green), with output powers reaching up to -1dBm/channel. The tilt on the signal corresponds to the roll-off in amplifier gain at longer wavelengths. The lasers clearly have high side-mode suppression ratios, exceeding 40dB in most cases. Note that some of the passive components in the transmitter have considerably unbalanced losses for each wavelength channel, which also results in the power non-uniformity of different channels.

The HC-PBGF used had a 19 cell core design and was 1.15km long, with a minimum loss of 2.8dB/km at 1990nm (Fig. 3) and a 3dB bandwidth of 85nm. The fiber was spliced at both ends to standard SMF via a short length of buffer fiber used to reduce mode-field mismatch between the SMF and HC-PBGF and to enable optimum launch into the fundamental mode[9]. The total insertion loss, including the fiber attenuation and all splice losses, was 10.5dB at 1987nm. Fig. 2 also shows the spectrum after transmission (black), showing only the excess loss of the fiber arrangement. The very narrow dips are absorption features due to the presence of carbon dioxide and water vapour within the hollow core; these can be reduced significantly or even eliminated by purging the fiber with dry gas[10]. However, the centre wavelengths of the WDM channels were detuned by no more than 0.4nm in order to avoid these absorption regions in the current experiments. The polarisation dependent loss remained below 0.3dB.

An optically pre-amplified receiver was implemented for the first time at 2µm, utilizing a variable attenuator to control the input power to the $2^{nd}$ TDFA, and hence to vary the optical signal-to-noise ratio (OSNR), measured within 0.1nm bandwidth. In order to select each wavelength channel, a commercially available tunable filter was used, with a 3-dB bandwidth of ~1.6nm, sufficient to select each of the WDM channels. A $3^{rd}$ TDFA was needed in order to guarantee a constant optical power to the receiver PD for all OSNRs, compensating for the lower gain of the TDFAs between 1990 and 2010nm. The gain of this $3^{rd}$ TDFA was adjusted to guarantee a fixed power level of -2dBm at the 12GHz-bandwidth detector for all wavelengths. The electrical signal was amplified before either a 16GHz, 100GS/s sampling scope (DPO), or an error detector (ED), depending on the channel measured.

## Results and Discussion

The performance of the 2µm WDM system was analyzed in terms of bit error rate (BER) against OSNR either at back-to-back, or after the 1.15km of HC-PBGF. Fig. 4(a) shows the performance of 8.3Gbit/s 4-ASK Fast-OFDM channels, with OSNRs of 30.8dB or below to achieve a BER of $1\times10^{-3}$ (FEC limit). A spread of about 2dB between channels was observed, with transmission penalties varying from 1.1 to 1.4dB only. The spread in OSNR requirement for the directly modulated channels is probably due to variation in the RF bandwidths of each of the lasers, with better BER performance for those with larger bandwidths. In addition, the number of OFDM subcarriers and the power ratios of each were not fully optimized for transmission, again causing a variation in the BER performance.

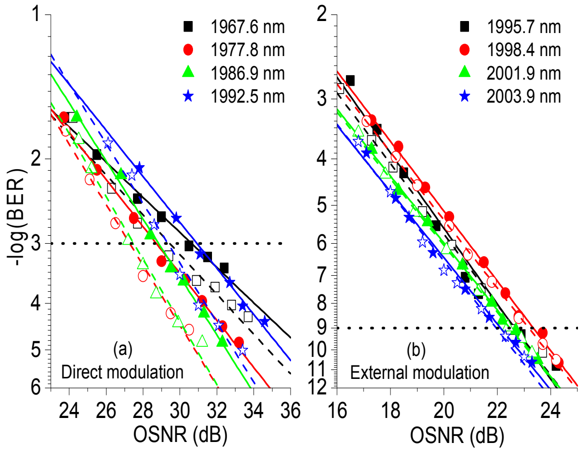


**Fig. 4:** BER performance vs. OSNR for back-to-back (open symbols) and after transmission over 1.15 km HC-PBGF (closed symbols) for (a) directly modulated and (b) externally modulated channels.

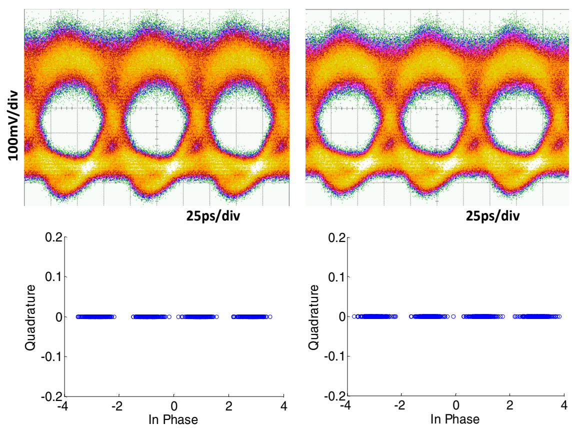


**Fig.5:** (top) Eye diagrams of NRZ-OOK externally modulated channel (1995.7 nm) and (bottom) constellation diagrams for 4-ASK Fast-OFDM directly modulated channel (1986.9 nm), both for (left) B2B and (right) over HC-PBGF

Fig.4 (b) illustrates the performance of all four NRZ-OOK externally modulated channels. The maximum OSNR to achieve a BER of $1\times10^{-9}$ was 23.3dB, with a spread of ~1dB between channels. This is most likely due to the amplifier gain tilt as shown in Fig. 2. It should be noted that, when transmitting over HC-PBGF, the transmission power penalty is negligible for all four externally modulated channels. Fig. 5 (right) illustrates that the eye diagram for an externally modulated channel is quite open, and that the constellation diagram for a directly modulated channel is very clear after 1.15 km HC-PBGF transmission, showing no distortion after transmission in both cases.

## Conclusions

We have presented WDM transmission at 2μm over 1.15 km of low loss HC-PBGF. A record of 81Gbit/s using 4× 7.7Gbit/s 4-ASK Fast-OFDM directly modulated channels and 4× 12.5Gbit/s NRZ-OOK externally modulated channels have been demonstrated, spanning an extended waveband of 36.3nm. This study illustrates the rapid growth in maturity of technologies for future communication system applications at 2μm.

## Acknowledgements

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