

# Challenges and Opportunities for Transmission in the 2 $\mu$ m Waveband

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**Abstract** *This talk will review transmission at 2 $\mu$ m to date, highlighting the challenges in opening a new transmission window for optical fibre communications, but creating new exploratory opportunities in alternative applications.* ©2023 The Author(s)

## Introduction

At ECOC 2012, our teams working within the EU [FP7 project MODEGAP](#) shown fibre transmission at 2  $\mu$ m for the first time with two post-deadline papers [1]-[2], opening up a decade of novel research from device development to systems applications.

The idea of opening a new transmission window further in the infrared, however, dates back to the 1980s [3]. This was a time, pre-EDFAs, where fibre transmission systems were struggling with high fibre losses and nonlinearities; but soon overhauled by the introduction of EDFAs to commercial systems in the mid-80s. C-band was then deemed “infinite”, and it would take nearly another two decades for operators to seriously consider L-band as a means to increase capacity in installed systems. But it wasn’t until the new capacity-hungry applications of the 00s, that serious consideration to increase capacity and spectral efficiency needed to be investigated further. The terminology “capacity crunch” soon followed [4], awakening the community that standard single mode fibres (SMF) limitations are again on our doorsteps, and new pragmatic ideas are needed. The immediate thought, and very much researched still today, is to extend the use of SMF as much as possible, given the cost of new fibre installation (or replacement), and hence the utilisation of alternative wavelength bands beyond C+L (e.g. S-, O-), so called ultra-wideband transmission, being a good choice [5], albeit with its own challenges, specifically related to Raman effects, nonlinearities, and availability of essential devices (e.g. multi-band amplifiers, ROADMs etc). Looking into the future, however, SMF is likely to be superseded by a new fibre type to enable very high capacities and low latency. One of the biggest contenders is special division multiplexing (SDM) using multi-mode and/or multi-cores fibres, as seen by the enormous research efforts in the past decade, with record capacities and spectral efficiencies shown [6], including initial installation efforts [7]. SDM comes with its own challenges, of course,

such as standardisation of the fibre technology, or on coupling, or on efficient amplification, on the additional signal processing required etc. Simultaneously, in the past decade, hollow-core fibres became very prominent, although in existence since the early 90s [8]. Hollow core photonic bandgap fibres (HC-PBGF) consistently shown significant developments [9] in reducing loss, by improving fabrication processes, in connectivity/splicing to standard solid core fibres, and in the development of very long lengths of fibre, which were key concerns from the telecom community. It was within this context that the idea of opening a new transmission window at 2 $\mu$ m risen, to explore the theoretical low loss limit of HC-PBGF at this waveband, and pushing the applications of semiconductor device technologies further in the infrared.

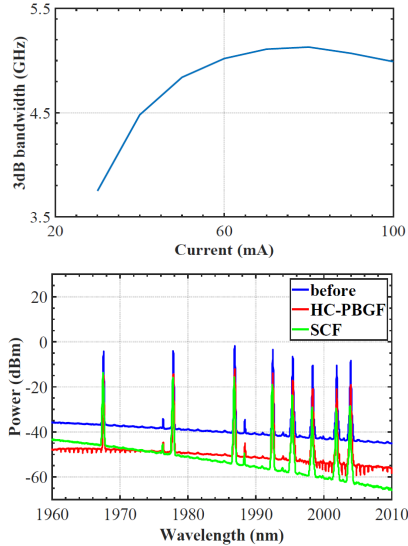
In this invited talk we will focus on the device technologies required to enable opening a new transmission window at the 2 $\mu$ m waveband, with fibre technologies out of scope of this paper as it is extensively studied elsewhere. It is important, however, to note that anti-resonant hollow core fibres (NANFs) [10] are potentially the most important fibre development in the last decade, enabling true super-broadband transmission with low loss, tailored dispersion, ultra-low-nonlinearities and low latency.

The challenges we faced and are still overcoming today at 2  $\mu$ m can be replicated to any other alternative transmission band, given the scarceness of optical devices that perform to the same standards as C-band devices (i.e. lasers, detectors, modulators, amplifiers, ROADMs), albeit solutions are now starting to slowly emerge in the market.

## Transmission at 2 $\mu$ m

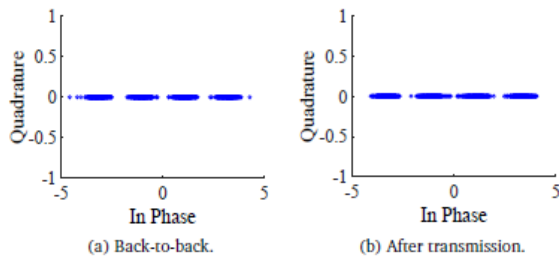
One of key elements [11]-[12] for enabling transmission at 2 $\mu$ m is certainly the availability of telecom-grade lasers, with relative low linewidths and enough power. Although quantum-cascade lasers (QCL) emitting at longer wavelengths have been around for a long-time, the stability required for telecommunications prevent their use, and

hence novel laser technologies based on InP (InAlGaAsP) materials are welcomed. In this case, the key principle to enable emissions at longer wavelengths is to increase the In content, straining or relaxing the lattice, and hence shifting the bandgap, with careful design of epitaxy processes.



**Figure 1: (upper) 3dB  $S_{21}$  laser response for different bias currents. (lower) 100 Gbit/s WDM transmission spectra.**

Emissions between 1.8 and 2.1  $\mu\text{m}$  were readily demonstrated with InP-based discrete-mode slotted Fabry-Perot lasers [13]. Modulation can be achieved with direct modulation, but with the drawback of a limited  $S_{21}$  frequency response, as exemplified in Figure 1(upper).

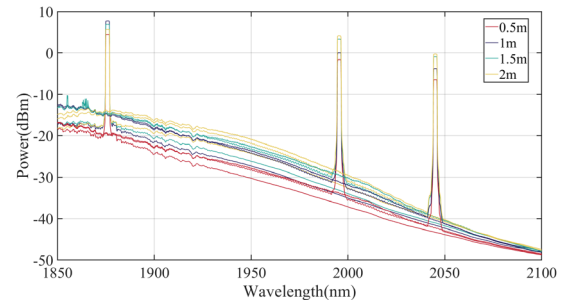


**Figure 2: 4ASK Fast OFDM constellation diagrams before and after transmission.**

Given the limitations on frequency response at the time, we have shown an overall 100 Gbit/s transmission by externally modulating four lasers with non-return-to-zero (NRZ) on-off keying (OOK) at 15.7 Gbit/s, and directly modulating four lasers with 4-amplitude shift keying (4-ASK) Fast-OFDM, each at 9.3 Gbit/s (excluding 7% FEC overheads), spanning a total optical bandwidth of 36.3 nm [14], as shown in Figure 1(lower). The comparative constellation diagrams before and after transmission for one of the channels is depicted in Figure 2, showing no penalty after transmission, as expected, given the optimised power and signal-to-noise ratio of the system.

Higher order modulation formats were also shown at 2  $\mu\text{m}$ , such as 64QAM OFDM [15] and PAM4 [16]. The requirement for external modulators is a key developmental need, with InP-based modulators [17], and more recently high-speed thin-film lithium-niobate-on-insulator optical modulators [18], essential contenders for higher throughput.

As in any other transmission band, the availability of low-noise optical fibre amplifiers is key, and the 2  $\mu\text{m}$  waveband can explore Thulium and Holmium-based fibres for amplification [19]. For example, we have shown that optimising the length of Thulium-fibre can improve the gain in the different wavelength ranges, as shown in Figure 3. Here amplification improvements at long wavelengths are seen when increasing the fibre length, due to reabsorption of shorter wavelengths by unexcited Thulium [20]. This means that each optical amplifier must be carefully designed for the wavelength region of interest.

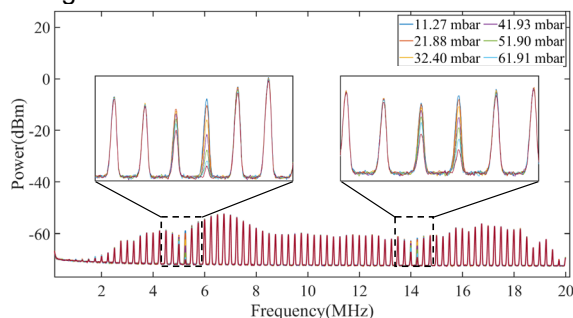


**Figure 3: Spectra of Thulium-doped fibre amplifier for different fibre lengths, maintaining 500 mW pump power.**

The 2  $\mu\text{m}$  waveband provides an opportunity to work in a Silicon photonics (SiP) sweet-spot, where two-photon absorption is significantly reduced, and Kerr nonlinearities peaks, hence minimising the overall loss and creating opportunities for nonlinear devices. As Si is transparent at 2  $\mu\text{m}$ , it is the ideal material to integrate passive components and waveguides to actives, in particularly with techniques such as transfer printing (TP) [21]. For example, TP can explore recent developments in GaSb lasers [22] for the 2-3  $\mu\text{m}$  wavelength range; integration of chalcogenide materials has shown potential [23]; cascaded MZ demultiplexers operating at 2  $\mu\text{m}$  were also shown [24]; and quite promising is the work on nonlinear materials enabling wideband wavelength conversion (or wavelength translation) [25] that could impact how to enable transmission not only in the 2  $\mu\text{m}$  waveband, but also extending to other transmission bands while terminals remain in the C-band.

## Opportunities beyond optical fibre transmission

Many of the technologies here exemplified and developed, from devices, fibres to subsystems, are showing potential disruptive impact for environmental and health sensing, in particularly exploring the  $2\mu\text{m}$  waveband. For example, this is the case for Carbon Dioxide ( $\text{CO}_2$ ). Although high absorption cross-section lies at the  $3\text{--}4\mu\text{m}$ , the less explored  $2\mu\text{m}$  region may enable multiple molecules to be detected simultaneously; and, with the availability of semiconductor devices operating in this region, with efficient power consumption, it could open a new frontier in sensing technologies utilising photonic integrated circuits. We have recently shown the use of lasers and injection locking, developed for optical fibre transmission, expanded in a coherent dual frequency comb at  $2.002\mu\text{m}$  [26], to enable detection of  $\text{CO}_2$ , with high resolution absorption profiles captured with millisecond acquisition times [27]. Figure 4 shows one of these measurements of  $\text{CO}_2$  absorption around  $2002\text{ nm}$ . The FSR of the comb used here was  $1\text{ GHz}$ , with measurement realised in a single pass over  $50\text{ cm}$  with only  $\text{CO}_2$  present in the cavity. This is an exciting result that could lead to important applications in monitoring climate change.



**Figure 4:**  $\text{CO}_2$  detection at  $2.002\mu\text{m}$  wavelength with a DFC assisted with injection locking, performed in an atmospheric chamber of  $50\text{ cm}$  with varied pressure.

Further applications likely to be shown in the near term is in medical sensing, but also in free space communications (or in space communications), as the solar radiance is diminished at  $2\mu\text{m}$ , hence being a great contender for near loss-less free-space transmission [28].

## Conclusions

Here we shown examples of challenges opening a new transmission window, in particular developing novel efficient device technologies. As in the past, opening a new transmission window required simultaneous fibre and device development, and the visionary experiments from 2012 opened this possibility. The future of  $2\mu\text{m}$

is promising and exciting, because not only enables optical fibre transmission exploring novel fibre technologies, it also allows exploitation of such technologies in other application areas, such as environmental and biomedical sensing.

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