Invisible to the human eye, mid-infrared (mid-IR) light at wavelengths of 2 μm and beyond is increasingly becoming the center of attention in photonics as many new exciting scientific discoveries and applications with radical impact on such diverse fields as health care, sensing, telecommunications and material science are expected from the availability of convenient, powerful and broadband laser sources in this emerging waveband. However, current laser sources in the mid-IR do not yet fulfill these conditions. Fibre lasers are today's standard in many end-user applications due to their ease-of-use, compactness and reliability, but they are still in their infancy in the mid-IR, because the conventional fibre material, silica glass, is not transparent for wavelengths much beyond 2 μm.

With the ADMIRATION project we targeted to advance mid-IR photonics along the path from lab curiosity towards widespread interdisciplinary application by developing real-world applicable, broadband mid-IR laser sources based on optical fiber technology. Our approach consisted of a three-step strategy: (i) the development of a strong suite of versatile and flexible Thulium-doped fiber amplifier (TDFA) systems, based on conventional silica fiber technology and emitting at wavelengths around 2 μm; (ii) the design and fabrication of specialty "soft glass" fibers (SF), made from mid-IR transparent glasses such as fluoride, germanate or chalcogenide, which convert the initially narrowband laser light of the TDFA pump systems into a broadband "supercontinuum" (SC) that spans far into the mid-IR, generated by nonlinear effects that occur when sufficiently high optical powers propagate inside the SF; and (iii) the implementation of the newly developed sources in 4 key application areas: telecommunications, ultra-short pulse generation, bio-photonics, and metrology.

Within the course of the project, we pioneered the development and extensive characterization of TDFAs as high performance amplifier for potential future telecommunication networks operating at wavelengths around 2 μm. By demonstrating high gain, low-noise amplification in the 1720 – 2050 nm window and developing compact and efficient diode-pumped versions, our TDFAs are truly analogous to the current Erbium-doped fiber amplifiers (EDFAs), but capable of operating over more than twice the bandwidth. Hence they represent an attractive route towards significantly enhanced transmission bandwidths by offering the potential to amplify a large number of additional wavelength-division multiplexed communication channels. In addition, the TDFA bandwidth overlaps with the low-loss window of hollow-core photonic bandgap fibers (HC-PBGF), which are promising candidates for a new generation of transmission fibers due to their ultralow nonlinearity and a more than 30 % faster transmission speed compared to conventional solid fibers. In collaboration with researchers working on the EU-funded MODEGAP project, we could demonstrate the transmission of TDFA-amplified data channels at 2 μm over HC-PBGF for the first time. These ground-breaking results represent fundamental steps towards assessing radically novel fiber solutions for next generation transmission systems.

This TDFA technology also allowed us to create new possibilities and set new records in high power short- and ultrashort pulsed fiber laser systems. By combining semiconductor laser diodes at 2 μm and multiple TDFA stages in a master oscillator power amplifier (MOPA) design (Fig. 1 (a) top), we constructed extremely versatile laser systems that can switch between the generation of picosecond pulses with record peak powers up to 130 kW and user-defined nanosecond pulse shapes with millijoule energy levels by simple electronic control. This flexibility makes these diode-seeded TDFA systems arguably the most practical and flexible approach currently available to generate high power pulsed laser radiation in the 2 μm wavelength region, enabling applications in nonlinear frequency conversion further into the mid-IR region and material or tissue ablation.

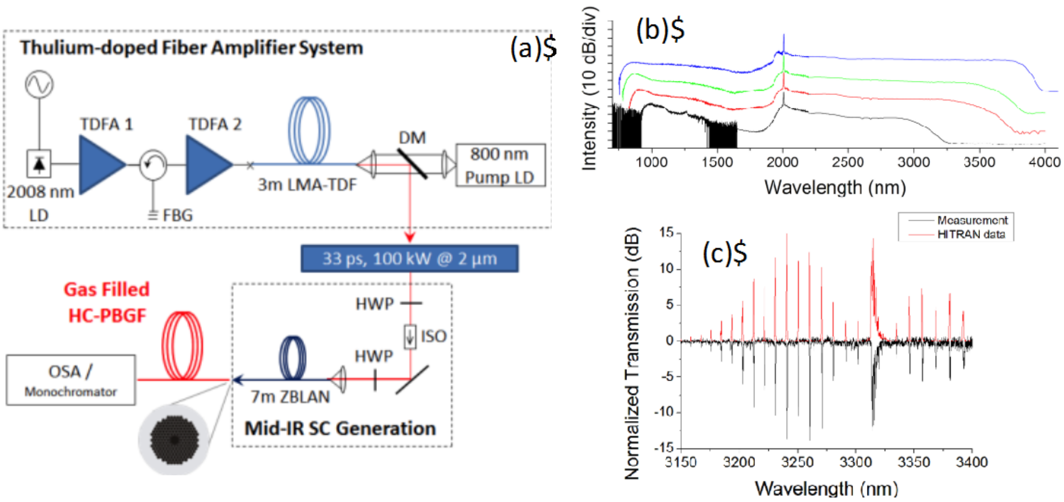

Fig. 1 (a) Schematic setup of high sensitivity fiber-based gas sensing. The high power diode-seeded Thulium-doped fiber amplifier (TDFA) system is followed by a mid-IR supercontinuum (SC) generation stage in nonlinear ZBLAN fiber and a hollow-core photonic bandgap fiber (HC-PBGF) filled with the gas under test. (b) Examples of generated mid-IR SC spectra spanning 750 – 4000 nm. (c) Absorption spectrum of 1000 ppm methane gas in nitrogen detected in 1.3 m of HC-PBGF (bottom) and comparison with theoretical data (top).

Using these TDFA MOPA systems and SC generation in a matched highly nonlinear fluoride (ZBLAN) glass fiber, we constructed a broadband laser source spanning from 750 – 4000 nm with Watt-level average power, excellent spectral flatness and stability (Fig. 1 (a, b)). This SC source is ideally suited for broadband mid-IR spectroscopic measurements with uniform spectral sensitivity and high signal-to-noise ratios in wavelength regions where various hydrocarbons, hydrochlorides and commonly used solvents display strong absorption features and that therefore can be fingerprinted using their unique signatures. For instance, gases such as methane and ethane exhibit strong fundamental absorption peaks in the region between 3 – 4 μm and have been identified as biomarkers in breath analysis, a non-invasive health screening technique. In this context we demonstrated first steps towards high sensitivity fiber-based gas sensing by filling a 1.3 m long piece of a in-house developed ultra-low loss HC-PBGF guiding at mid-IR wavelengths with methane gas and recording a transmission spectrum using our SC source (Fig. 1 (c)). We could establish a detection limit of 0.9 ppm – several orders of magnitude lower than previous reports using fiber-based systems. Detection of even lower concentrations in mid- to low ppb regime over longer fiber lengths is certainly feasible. This demonstrates that our 2 μm diode-seeded MOPA pump systems followed by a mid-IR SC generation stage and a detection stage in low-loss HC-PBGF is certainly a promising approach for the realization of compact and versatile multi-band, multi-element spectroscopic measurement devices in the mid-IR for healthcare, environmental, and security applications.

This project also demonstrated the first steps towards broadband coherent and ultrafast SC generation in the mid-IR based on so-called “all-normal dispersion” (ANDi) fibers, setting the foundations in place for versatile fiberized optical frequency combs for high precision spectroscopy and widespread ultrafast photonics applications in this waveband. In contrast to the SC generation process in conventional fibers, which is based on the temporal break-up of the injected pulses and highly sensitive to noise, ANDi fibers selectively suppress noise-amplifying nonlinear dynamics and preserve the injected ultrashort pump pulses. In collaboration with partners in Poland and the USA, two ANDi fiber implementations could be realized that in combination demonstrate ultrafast coherent SC generation in the bandwidth 900 – 3400 nm. While further characterization is necessary, numerical simulations show that these spectra can support a single cycle pulse in the time domain. Such a relatively simple few-cycle pulse source in the mid-IR gives rise to exciting new possibilities in femtochemistry, nonlinear bio-photonic imaging, and even the generation of coherent X-ray and attosecond pulses via high harmonic generation.