

Fig. 8. Application of TDFAs in optical fiber communications at 2 μm . (a) Amplified spectra and corresponding noise figure (NF) of diode-pumped TDFAs based on the design of the pre-amplifiers discussed in section II.B. By combining TDFA-S/C/L optimized for short, central, and long waveband operation, respectively, high-gain low-noise amplification covering the entire Thulium gain bandwidth in the range 1720 – 2050 nm can be achieved. (b) Cross section and loss spectrum of the HC-PBGF used in recent 2 μm data transmission experiments, overlapped with the output of TDFA-L showing the amplified data channel. The transmission bandwidth of the fiber matches well with the gain bandwidth of the TDFA [47].

at 1 μm and 1.5 μm [19, 34, 35], but has never been demonstrated before at 2 μm .

Fig. 6 (b) shows the calculated input pulses required to obtain 0.5 mJ output pulses with a selection of user-defined shapes and compares them with the experimental measurements, obtained by direct modulation of the seed diode using the AWG. There is an excellent agreement between targeted pulse shapes and measured profiles. Further energy scaling beyond 0.5 mJ in MOPA A is limited by the low peak power available directly from the diode (~ 5 mW). For the compensation of gain saturation at higher pulse energy, strong shaping with a high dynamic range is required, which reduces the seed average power to impractically low levels with our current diodes.

MOPA B allows energy scaling to 1.0 mJ and beyond by making use of the EOM as a pulse shaping device. In this case the seed diode is set to emit square pulses of 300 ns duration. These initial pulses are then amplified in the first pre-amplifier without distortion, from which the EOM, directly driven by the AWG carves 100 ns pulses with the required pulse shape. This ensures sufficient seeding of the subsequent amplifiers and enables us to operate at a lower repetition rate of 12.5 kHz.

Fig. 7 shows the output pulse shape and spectrum at 1.0 mJ pulse energy. The extreme gain reshaping occurring at these high energies is clearly compensated, although the profile does not exactly match the desired square shape due to the limited extinction ratio of the EOM (20 – 23 dB at 1950 nm). However, without shaping we observe the onset of stimulated Brillouin scattering (SBS) already at 0.25 mJ in this system, caused by the narrow linewidth of the seed in long pulse operation in combination with the high peak power of the amplified unshaped pulses. This clearly highlights the importance and effectiveness of the pulse shaping approach. The spectrum in Fig. 7 (b) is free of ASE or nonlinear signatures, confirming the potential for further energy scaling using EOMs with higher extinction ratio or acousto-optic modulators.

IV. APPLICATIONS

A. Next-generation telecommunication networks

The ever-increasing volume of internet traffic drives today's telecom networks rapidly towards their capacity limits [36-39]. Traditionally, research efforts in long-haul telecom networks have been focused on the 1.55 μm wavelength region defined by the amplification bandwidth of the EDFA and the low-loss transmission window of single-mode silica fiber (SMF). More recently, however, radical approaches in more exotic fiber types are actively being pursued to increase the transmission capacity per fiber, decrease fiber loss and nonlinearity and reduce signal latency [40-42], which may eventually justify a shift away from the traditional operating wavelengths.

TDFAs exhibit a gain bandwidth of about 30 THz, which is more than twice as large as the EDFA bandwidth (~ 12 THz for current C + L band) and is the broadest of all rare-earth doped fiber amplifiers [3]. 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 (WDM) communication channels. TDFAs based on the design principles discussed in section II.B (Fig. 2) have now been extensively characterized in an optical communications context and were found to be a viable alternative to modern EDFAs [22]. Since diode-pumped versions have been developed [23], where the fiber laser pump source in Fig. 2 (a) is replaced by in-band pumping 1550 nm laser diodes, TDFAs have now truly reached a similar level of compactness, reliability and efficiency as current Erbium-based systems. In Fig. 8 (a), high gain low noise amplification over the entire Thulium gain bandwidth of more than 300 nm from 1720 – 2050 nm is demonstrated by combining three of these compact devices optimized for short, central, and long waveband operation, respectively. Based on these TDFA designs, a compact diode-pumped all-fiber thulium-doped laser with more than 250 nm of continuous tuning range could also be realized [25]. This recent maturation of the TDFA certainly confirms the practicality of 2 μm optical fiber communications from an amplifier perspective.

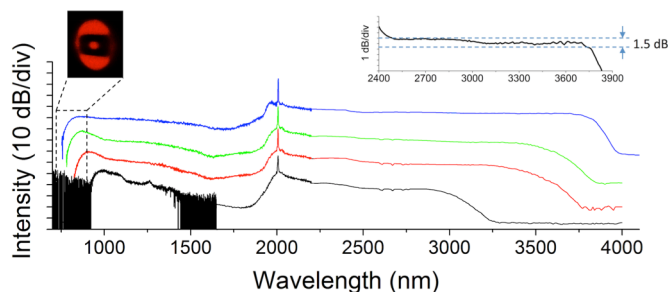


Fig. 9. Supercontinuum generation using high peak power picosecond pulses from MOPA A directly coupled into 7 m of highly nonlinear ZBLAN fiber. The spectra were generated using pulse energies of 185 nJ (black), 300 nJ (red), 600 nJ (green), and 1100 nJ (blue); offset for clarity. The insets show the exceptional flatness of the mid-IR part of the broadest spectrum, and the far-field multi-mode beam profile of the ZBLAN output at visible wavelengths. The fiber is single-moded for wavelengths above ~ 2800 nm [69].

The development of low loss transmission fibers will however be the key factor determining whether $2\ \mu\text{m}$ communications will ultimately outperform current $1.55\ \mu\text{m}$ systems. Hollow-core photonic bandgap fibers (HC-PBGF) are promising candidates for such a new generation of transmission fibers due to their ultralow nonlinearity and a more than 30 % faster transmission speed compared to conventional solid fibers [41]. These properties originate from the light guidance in their hollow core with minimal overlap (as low as 0.1 %) with the surrounding silica glass structure [43]. This low overlap factor is also responsible for reducing infrared absorption and shifting their minimum loss to wavelengths around $2\ \mu\text{m}$ – conveniently coinciding with TDFA territory [44, 45].

In a recent proof-of-principle experiment, the error-free transmission of an amplified 8 Gbit/s data channel at $2\ \mu\text{m}$ over 290 m of HC-PBGF was demonstrated for the first time [46, 47]. The fiber's more than 150 nm wide transmission window with minimum loss of 4.5 dB/km overlaps well with the amplification bandwidth of TDFA-L discussed in II.B, as shown in the comparison in Fig. 8 (b). WDM transmission of 4 data channels was later reported using the same fiber and amplifier [48]. Interestingly, many of the building blocks of the MOPA systems described in this paper were also used for these transmission experiments, clearly showing the beneficial interdependence of high power fiber laser and telecom system research.

Currently, strong efforts are being directed towards determining the intrinsic loss limits of HC-PBGF and fabricating fibers with broader transmission windows and loss values closer to those of conventional SMFs [49]. However, it is now clearly established that HC-PBGFs can meet the challenging requirements of modern data modulation formats and 30.7 Tbit/s (96x320Gbit/s) dual polarization (DP)-32QAM coherently detected transmission over HC-PBGF at $1.55\ \mu\text{m}$ has been demonstrated [50]. They also offer the possibility to implement novel capacity-enhancing techniques such as space division multiplexing (SDM) [40], as impressively shown by a record capacity of 73.7 Gbit/s through a combination of dense WDM and SDM using the

three lowest order modes of a HC-PBGF [51]. The development of low-loss splicing techniques using standard equipment further confirms the practicality of these fibers [52, 53]. Certainly, the combination of TDFAs and HC-PBGFs operating at $2\ \mu\text{m}$ is one of the most radical approaches for next-generation telecom networks, but also one of the most exciting ones for high power fiber laser research, as the development of new laser diodes, low-loss components, high-performance amplifiers and low-nonlinearity beam delivery fibers can be expected at this emerging waveband.

B. Mid-IR supercontinuum generation

The high peak powers and short pulse durations emitted by our MOPA systems in gain-switched picosecond mode are ideally suited for nonlinear frequency conversion further towards mid-IR wavelengths. Supercontinuum generation (SCG) in nonsilica fibers made from nonlinear mid-IR transparent glasses (e.g. fluoride, tellurite, or chalcogenide) is a promising approach to meet the increasing demands for broadband, high-brightness mid-IR radiation in various application areas, e.g. molecular fingerprinting, chemical sensing or gas detection (see section IV.C) [54, 55]. Of all possible materials, heavy metal fluoride glass (ZBLAN) is currently the most attractive choice for constructing practical SCG sources due to its high transparency up to $\sim 4.5\ \mu\text{m}$ wavelength, the maturity of the fiber fabrication technology and the commercial availability of highly nonlinear ZBLAN fibers with the required small core diameters. Consequently, SCG in this fiber type has been demonstrated with numerous pumping schemes, predominantly using either femtosecond or nanosecond pulse durations [56-62].

From the perspectives of compactness, reliability, versatility and cost-efficiency, semiconductor laser diodes as master oscillators coupled with fiber amplifiers are the ideal choice of pump system for SCG. They offer a significant control over the properties of the generated SC through their capability to deliver wide ranges of adjustable pump pulse parameters, which has contributed to their scientific and commercial success in the near-IR and visible wavelength regions [63-66].

ZBLAN fibers typically have zero-dispersion wavelengths (ZDWs) between $1.65 - 1.9\ \mu\text{m}$. Pumping at wavelengths longer than the ZDW in the anomalous dispersion region is advantageous for efficient SCG, and $2\ \mu\text{m}$ pumping in particular leads to an optimization of both bandwidth and conversion efficiency [67]. Prior to this work, however, diode-pumped mid-IR SCG sources had to be based on 1550 nm seed-diodes and therefore had to rely on either nonlinear methods or the use of intermediate pulse-pumped TDF laser cavities to convert to longer pumping wavelengths [55, 56, 68]. Using the MOPA systems presented here, it is now possible to implement the direct picosecond diode-pumping of ZBLAN fibers at $2\ \mu\text{m}$, which represents a significant improvement in terms of system simplicity, reliability, and stability compared to previous diode-pumped mid-IR sources [69].

Fig. 9 shows the resulting SC spectra when various pulse energies emitted by MOPA A are directly coupled into a 7 m

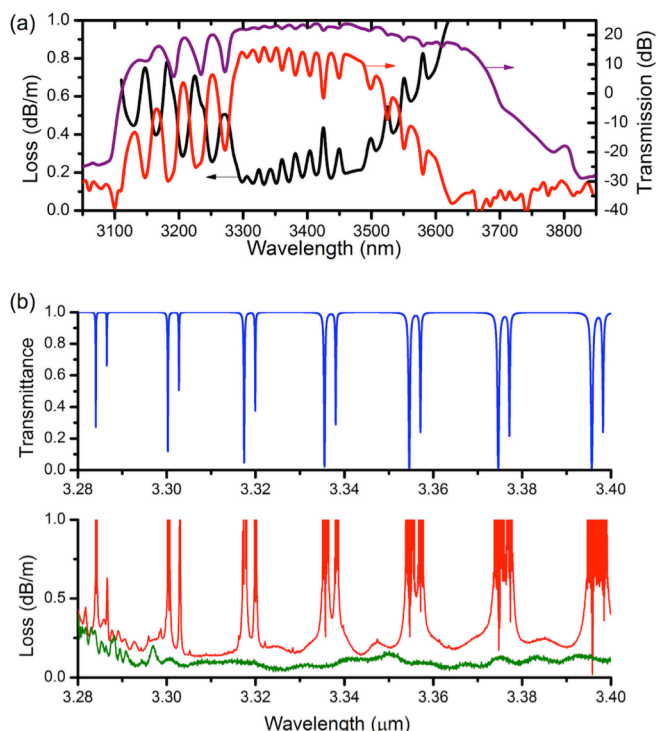


Fig. 10. Low-loss, wide bandwidth mid-IR guidance in silica-based HC-PBGF. (a) Transmission through 5 m (purple), 58 m (red), and corresponding attenuation calculated from cutback measurement (black). (b) HCl gas absorption spectrum from HITRAN database (top) and high resolution (0.2 nm) attenuation measurements before and after purging the fiber with argon. The peaks in the attenuation spectrum can clearly be attributed to the presence of HCl gas outgassing from the raw materials used in fiber fabrication. All spectra were taken using the mid-IR SCG source described in IV.B [80].

long commercial ZBLAN fiber (Thorlabs, 9 μm core diameter, 0.25 NA). The maximum spectral bandwidth of more than two octaves spanning from 750 – 4000 nm is reached for 1.1 μJ pump pulses. Further broadening was limited by the attenuation of the particular fiber in use. The spectra exhibit a remarkable flatness in the mid-IR with a power variation as low as 1.5 dB over a 1300 nm wide spectral range from 2450 – 3750 nm, as shown in the inset of Fig. 9.

The total SC average power is up to 1.1 W at 1 MHz repetition rate, with more than 21% (235 mW) at wavelengths above 2500 nm. Further average power scaling is straightforward by increasing the repetition rate of the pump system. As shown in Fig. 4 (a), MOPA A can deliver the necessary pulse energy for maximum spectral broadening (1.1 μJ) up to repetition rates of more than 15 MHz, enabling total SC power in the order of 10 W.

The high degree of spectral flatness of the generated SC is unprecedented in this wavelength region. Combined with the high average output power and minimal mid-IR power fluctuations of less than 0.5 dB over a 30 minute interval the system enables 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. This will exemplarily be shown in the following section.

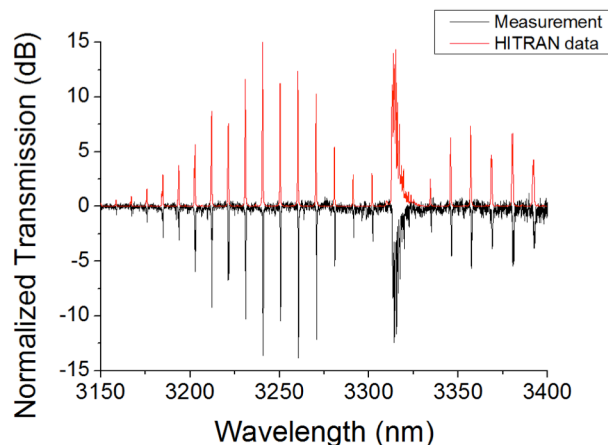


Fig. 11. Broadband, high quality mid-IR methane detection using the mid-IR SCG source from IV.B and the HC-PBGF from Fig. 10. The figure shows a high resolution (0.2 nm) transmission spectrum (black, baseline subtracted) recorded through 1.25 m HC-PBGF filled with a mixture of 1000 ppm methane in nitrogen. The absorption spectrum from the HITRAN database (red) is shown for comparison (mirrored on the baseline for clarity).

C. Mid-IR gas detection in hollow-core fibers

One of the main attractions of the mid-IR spectral region is the large number of molecules that undergo strong characteristic vibrational transitions in this domain and that can therefore be fingerprinted using their unique absorption signatures [7]. The highly sensitive detection of mid-IR absorption peaks is therefore expected to enable many local and remote sensing applications in environmental control, security, and healthcare industries. For instance, gases such as methane, ethane, and acetylene exhibit strong fundamental absorption peaks in the region between 3 – 4 μm and have been identified as biomarkers in breath analysis [70]. This non-invasive health screening technique aims to identify and quantify volatile components in human breath, which provide key information about physiological processes and enable early-detection of diseases such as renal failure, cystic fibrosis and cancer [71, 72]. However, low concentrations of multiple elements need to be detected simultaneously, which requires sensitive and broadband detection methods.

HC-PBGFs offer an excellent platform to observe weak gas-light interactions due to their tight modal confinement in the hollow core combined with their low-loss guidance. Filled with the gas under test, the hollow core fiber geometry allows extremely long interaction lengths and therefore the probing of weak gas absorption lines and low concentrations that would otherwise be difficult to observe using bulk approaches [49]. In addition, HC-PBGFs are particularly suitable for achieving small device footprints due to their low sensitivity to macro-bending such that tight coils can be formed with virtually no loss penalty [73]. Note that other air-guiding fiber geometries including hollow waveguides, anti-resonant fiber, and Kagome fibers exhibit substantially higher bend loss [74]. This is a critical issue for the design of practical sensing devices where long path lengths combined with small device form factors are required.

Most gas detection measurements in hollow core fibers to date have used the first overtone absorption lines in the near-IR [75-77], but the recent development of silica-based HC-PBGF with low loss over wide bandwidths in the mid-IR enables measurements on the much stronger fundamental absorption peaks [78, 79], which should increase sensitivity and specificity of the detection. The HC-PBGF with the lowest attenuation at mid-IR wavelengths reported to date was recently fabricated in-house and extensively characterized in [80]. Fig. 10 shows transmission and loss measurements of this fiber with (a) high dynamic range and (b) high resolution, both of which were enabled by using the SCG source described in the previous section. The measurement over a 5 m fiber length (purple line in Fig. 10(a)) shows that the bandgap extends from 3.1 to 3.8 μm and a cutback loss measurement (58 to 5 m) records a minimum loss of 0.13 (± 0.05) dB/m at 3.33 μm and < 1 dB/m transmission loss over a > 500 nm window, which overlaps well with one of the regions of interest for gas sensing, as mentioned above. In fact, many of the oscillatory features in the loss measurement can be attributed to HCl gas absorption lines, which are present in the fiber due to the use of chlorine to dehydrate the bulk silica glass used as raw material in fabrication (Fig. 10(b)). When removed by purging the fiber with argon gas, the fiber attenuation decreases to 0.05 (± 0.03) dB/m. These are particularly impressive numbers when compared to the bulk attenuation of silica, which is 100 – 600 dB/m in this spectral region [81], indicating an overlap of the guided mode with the silica cladding of only about 0.1%.

It appears that combining the powerful, flat, and stable mid-IR SCG source described in section IV.B with these low-loss guiding HC-PBGFs results in a sensitive broadband spectroscopic measurement device for gas detection in the mid-IR spectral region, as evident from the high dynamic range of the loss measurements and the high-resolution detection of the HCl absorption peaks. However, most of the HCl absorption peaks are saturated in this measurement due to the long fiber lengths used in the loss measurement.

In order to further demonstrate the capabilities of this system, we filled a 1.25 m length of the HC-PBGF with a mixture of 1000 ppm methane in nitrogen and recorded a high-resolution (0.2 nm) transmission spectrum over a broadband span of 250 nm from 3150 – 3400 nm using an optical spectrum analyzer (Yokogawa). In Fig. 11, the measurement with subtracted baseline is compared with the absorption spectrum from the HITRAN database, appropriately scaled to reflect interaction length, concentration and resolution of the measurement. The quality of the measurement and the agreement with theory is astonishing. Almost 15 dB OSNR could be achieved at the strongest absorption lines, and even the weaker lines could be resolved. In order to fully appreciate these results, they should be compared to earlier work in the mid-IR where only about 3 dB OSNR was obtained for the same methane concentration over a similar length of fiber and at a much lower resolution of 3 – 4 nm [79]. A minimum detection limit of 50 ppm was claimed in this work, which would clearly be much lower in our

system. More than sufficient power was transmitted through the fiber such that detection of even lower concentrations over longer fiber lengths is certainly feasible.

While more work has to be done in order to establish the minimum detectable concentrations and perform quantitative measurements (in preparation), these initial results demonstrate a substantial qualitative increase in both OSNR and resolution of the detected absorption lines compared to previous results. Consequently, the presented system consisting of our 2 μm diode-seeded MOPA pump systems followed by a mid-IR SCG 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 environmental, security, and healthcare applications.

V. CONCLUSION

Diode-seeded TDFA systems arguably offer the most practical and flexible approach currently available to generate high power pulsed laser radiation in the 2 μm wavelength region. Their capability to deliver pulses with vastly different parameters and shapes from the same laser system via straightforward electronic control is unmatched. From an applications point of view, this versatility of the laser system combined with the high stability of the pulse generation and amplification process are often more important than headline record power figures. All-fiber integration is also easy to envisage and would result in the robustness needed for commercial applications.

While we did not use very-large-mode-area fibers in order to keep the system as simple and compact as possible, large-pitch rod-type PCF fibers used in recent nanosecond work could easily be incorporated in our system and would substantially increase the observed nonlinear thresholds and enable further energy and peak-power scaling. Nonlinear pulse compression should also allow yet shorter pulses and higher peak powers.

Especially in conjunction with novel waveguide designs, such as highly nonlinear soft glass fibers or low-loss hollow core fibers, diode-seeded TDFAs are already enabling promising new research and technology pathways in the emerging waveband of 2 μm and beyond with substantial scientific and industrial impact.

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