Supercontinuum and gas cell in a single microstructured fiber

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We exploit both the high nonlinearity and the holey structure of microstructured fibers to combine a broadband light source and a gas cell in a single microstructured fiber. A broadband supercontinuum is formed by launching nanosecond pulses from a compact, Q-switched Nd:YAG laser into a microstructured fiber filled with acetylene. This continuum is self-referenced to the acetylene lines in the 1500 nm region. The performance of different index-guiding narrow-core microstructured fibers as nonlinear and host media is evaluated. The concept offers many possibilities and can be applied to various gases absorbing at different wavelengths. © 2005 Optical Society of America

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Microstructured fibers (MFs) have attracted considerable attention over the past few years due to their unique optical properties compared with those of standard optical fibers. These properties have led to the development of several applications such as broadband coherent light sources commonly referred to as supercontinuum (SC).[1] In addition to the tunability of the optical properties of MFs (dispersion and nonlinearity), the index-guiding mechanism and the holey structure offer a means to partially guide light in the cladding holes. The microstructured cladding of such fibers can be filled, e.g., with gases or liquids, thereby providing a long optical interaction path between light and the fluids in the holes. Recently, applications exploiting this special feature of index-guiding MFs have been explored theoretically[2,3] and experimentally.[4]

In this Letter, we demonstrate a compact, broadband optical source self-referenced to acetylene absorption lines in the 1500 nm region. The source is realized by launching ns pulses from a Nd:YAG laser into a narrow-core MF filled with acetylene. The gas-filled narrow-core MF functions as a nonlinear medium to generate the continuum and simultaneously provides a long interaction path between the evanescent field of light and gas. This results in light absorption at specific wavelengths in the output spectrum.[5] A numerical analysis of the formation of the continuum along the MFs is given through the use of an extended nonlinear Schrödinger equation.[6] The percentage of power located in the holes of the MFs is also investigated using a beam propagation method (BPM),[7] as this is a critical parameter affecting the efficiency of light–gas interaction.

The experimental setup employed to fill MFs with acetylene and to generate SC is illustrated in Fig. 1. The SC is generated by launching ns pulses from a compact, passively Q-switched Nd:YAG laser into a MF (Crystal Fibre A/S). The laser operates at the wavelength of 1064 nm and produces pulses ($T_{\mathrm{FWHM}} \approx 3$ ns) at a repetition rate of 30 kHz with a maximum average output power of ~120 mW. The output of the laser is not polarized. Coupling to the MFs is achieved with an achromatic lens (NA=0.3, $f=7$ mm), yielding a coupling efficiency of 20–30% depending on the core size and sealing (splicing or collapsing of air holes) of the fiber. The SC spectrum was monitored with an optical spectrum analyzer (Ando AQ6315B).

The MFs used in the experiments are referred to as MF-2.0 and MF-3.2 according to their core diameter. Their characteristics are summarized in Table 1, and their dispersion profiles calculated using the BPM are displayed in Fig. 2(a). Acetylene ($^{12}C_2H_2$) was selected since it has strong absorption lines in the 1500 nm region where optical telecommunications systems operate.[5] The purity of acetylene was specified by the manufacturer to be ~99%. The MF was butt coupled to a multimode fiber (MMF) with a gap of ~50 μm using a V-groove inside a vacuum chamber. A rotary pump was used for evacuating the fiber, and a conventional vacuum system was employed to fill it to a desired pressure. The input end of MF-2.0 was spliced to a standard single-mode fiber, whereas the microstructure at the input end of MF-3.2 was collapsed using a arc arc-fusion splicer (Ericsson FSU 995). In these ways, the fibers were perfectly sealed in the input end, while the output end was placed in the chamber to allow for filling of the fibers.

To obtain efficient light–gas interaction via an evanescent field, it is imperative to have a significant amount of the mode field overlapping the holes of the MF. Using the BPM, we investigated the amount of power effectively located within the holes of the MFs under test. The simulations show that the mode field overlaps only the first ring of holes see the inset in Fig. 2(b). The percentage of power within the holes versus wavelength for the two fibers plotted in Fig. 2(b) increases with wavelength and is reduced for large core sizes. This is explained by the facts that the mode-field diameter increases with wavelength

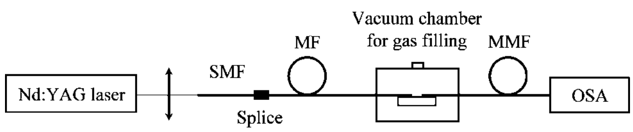

Fig. 1. Experimental setup. SMF, single-mode fiber; MMF, multimode fiber; OSA, optical spectrum analyzer.

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Table 1. Characteristics of Fiber Samples[a]

Characteristic	MF-2.0	MF-3.2
Core size (μm)	2	3.2
Λ (μm)	1.4	2.1
d/Λ	0.65	0.45
λ_{ZD} (nm)	750, 1670	945
Length (m)	15	19

[a] λ_{ZD}, zero-dispersion wavelength; d, air-hole diameter; Λ, pitch.

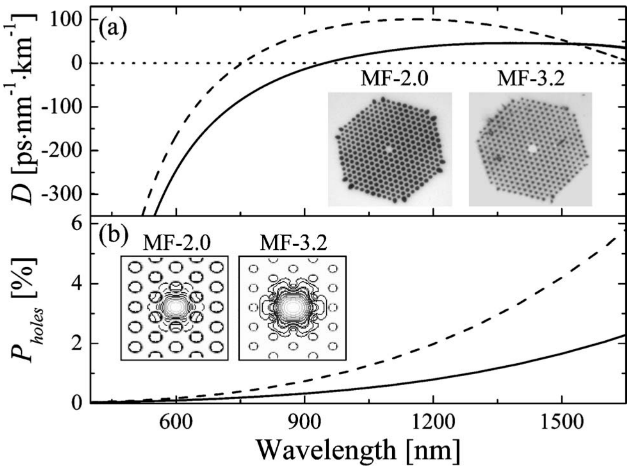

Fig. 2. (a) Dispersion profiles for MF-2.0 (dashed curve) and MF-3.2 (solid curve). Inset, microscope images of the fiber cross sections. (b) Percentage of the modal power located in the holes for MF-2.0 (dashed curve) and MF-3.2 (solid curve). Inset, simulated mode field at 1500 nm.

and that the mode images the microstructured cladding for smaller air-filling fractions. Near 1530 nm, where acetylene has strong absorption lines, the overlap is estimated to be 4.5% and 1.8% for MF-2.0 and MF-3.2, respectively. Therefore, narrower core dimensions should provide a larger overlap and thus result in stronger absorption lines. For example, small air-suspended rods could potentially provide larger overlap values. Nevertheless, the strength of the absorption line is a trade-off between the overlap and the formation of the continuum. In particular, the optical properties of the fibers are also expected to have a strong effect on the strength of the absorption lines. Indeed, for a given input peak power and pulse width the formation of the continuum depends on the dispersion and nonlinear coefficient of the fiber. In any case, it is of utmost interest to select the fiber so that the continuum formation is completed in a short as possible length of fiber to increase the interaction length between the frequency components of the SC and the gas. Optimization of the fiber characteristics to maximize the interaction length and gas–light overlap will be the subject of further study.

The measurements were first performed for MF-2.0 filled to a pressure of ~126 kPa. The filling process was monitored with a tunable laser, a wavemeter, and a photodetector. This allows for an accurate characterization of the strength of a particular absorption line as the wavelength of the laser can be swept through the line with a step size of 1 pm. After the filling process reached steady state, pulses from the Nd:YAG laser were launched into the fiber to generate the SC. The spectrum of the SC generated along the MF-2.0 is shown in Fig. 3(a) without (see inset) and with acetylene. For an average power of ~30 mW, the spectrum extends from 1 μm to beyond 1.7 μm. The onset of the SC generation can be explained as follows: the pump wavelength is located in the anomalous dispersion of the fiber, and therefore the SC formation is initiated by modulation instability[8] that breaks the broad input pulse into multiple short subpulses. These subpulses subsequently experience soliton self-frequency shift,[8] leading to expansion of the continuum toward the infrared. This scenario is confirmed through the simulations presented in Fig. 4. In the modeling, we used an extended nonlinear Schrödinger equation including the full propagation constant and Raman response of the fiber as well as the self-steepening effect.[6] For computation time considerations, the initial pulse width was chosen to be 1 ns and the fiber length 10 m. To allow for comparison with the experiments, the numerical simulations are plotted with the same resolution as used in the experiments. The simulation reproduces qualitatively the features of the experimental spectrum [see Fig. 4(a)] and confirms the formation of multiple short subpulses [see Fig. 4(b)]. Note that the losses of the fibers were not taken into account in the simulations, as they were not accurately known. The main consequence of neglecting the fiber losses is the absence of the water absorption peak in the simulation results.

Two dips are observed in the SC spectrum recorded with a 10 nm resolution [see Fig. 3(a)]. The first dip

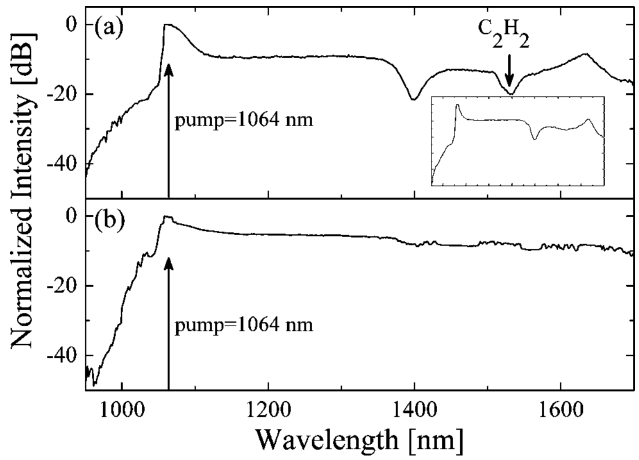

Fig. 3. SC generated in (a) MF-2.0 and (b) MF-3.2 filled with acetylene. Inset, SC without acetylene.

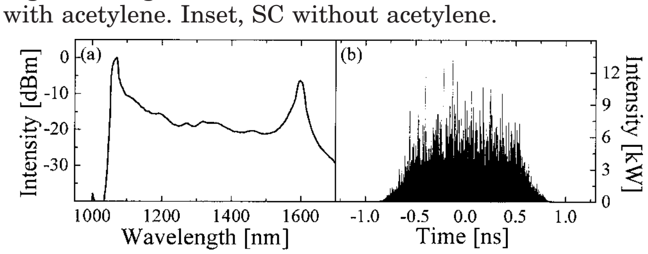

Fig. 4. Numerical simulations of the (a) spectrum and (b) time trace of the SC generated in MF-2.0.

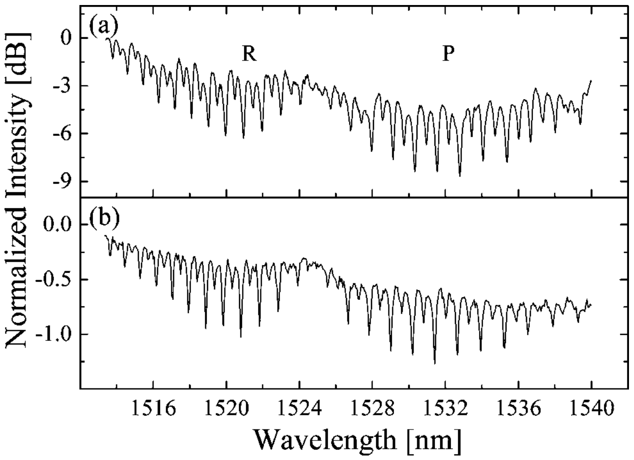

Fig. 5. High-resolution spectra of the P and R branches of $^{12}C_2H_2$ at 126 kPa in (a) MF-2.0 and (b) MF-3.2.

close to 1390 nm originates from the rather strong OH-absorption peak observed with MFs, and the second at 1530 nm is due to acetylene absorption.[5] By measuring only across the absorption range and using a higher resolution of 0.1 nm, the fine structure of the R and P branches of the $\nu_1 + v_3$ band of $^{12}C_2H_2$ can be resolved as illustrated in Fig. 5(a). The measurements were repeated for different pressures in the range ~25–130 kPa. The lines were still clearly visible at a pressure of 25 kPa, with a maximum strength of ~1.5 dB. Finally, the fiber was filled to a pressure of ~120 kPa and sealed at the open end by collapsing the cladding holes with the splicer. Closing the fiber at both ends yields a small fiber-based gas cell that can be combined with the pump laser to provide a compact and broadband reference source. The source was tested again after a period of three weeks with no noticeable change in performance.

Subsequently, MF-3.2 was filled to a pressure of ~126 kPa. In this case, the fiber was sealed at the input end with the splicer. After filling the fiber, the output end was immediately sealed using the same technique. The shape of the SC illustrated in Fig. 3(b) resembles the spectrum obtained with MF-2.0 with similar physical mechanisms leading to its formation. Nevertheless, no dip around 1530 nm is observed, indicating that the absorption lines are much weaker. A high resolution (0.1 nm) spectrum of the P and R branches of acetylene displayed in Fig. 5(b), however, shows that the lines are present and indeed substantially weaker than in the case of MF-2.0. This is as could be expected from the smaller nonlinear coefficient and overlap between the holes and mode field. In addition, a short exposure to air (~30 s) before sealing the output end of MF-3.2 could have slightly reduced the line strengths. Besides, we tested a 19 m long MF with a 4.8 μm core diameter, yielding a 0.5% fraction of power in the holes at 1530 nm. The SC extended substantially toward visible wavelengths due to the proximity of the zero-dispersion wavelength (1040 nm) with the pump wavelength but the absorption lines were very weak (~0.3 dB at 120 kPa).

We have demonstrated the combined action of a broadband light source and a reference gas cell in a single narrow-core MF. The approach provides a compact, simple, and cost-effective SC source that is self-referenced to the acetylene lines in the 1500 nm region. Such a source may find applications in the characterization of optical components, wavelength monitoring, calibration of measurement instruments, and as a sensor. The strength of the absorption lines can be enhanced by increasing the peak power of pulses or the fiber length. Furthermore, it is also possible to improve the gas-light overlap by utilizing a microstructured fiber with a narrower core and higher air-filling fraction. We also anticipate that the use of ps or fs pump lasers would result in enhanced absorption strength because of the longer interaction length, as supercontinua generated with these types of laser are typically formed within much shorter lengths. Moreover, a source with multiple reference bands at desired wavelengths can be realized by filling a fiber with various nonreactive gases at different partial pressures chosen according to their absorption strengths. Finally, we point out that the same technique could be applied to enhance the bandwidth of the supercontinuum by selecting a suitable nonlinear fluid.

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References

1. J. K. Ranka, R. S. Windeler, and A. J. Stentz, Opt. Lett. **25**, 25 (2000).
2. T. M. Monro, W. Belardi, K. Furusawa, J. C. Baggett, N. G. R. Broderick, and D. J. Richardson, Meas. Sci. Technol. **12**, 854 (2001).
3. J. M. Fini, Meas. Sci. Technol. **15**, 1120 (2004).
4. Y. L. Hoo, W. Jin, H. L. Ho, D. N. Wang, and R. S. Windeler, Opt. Eng.**41**, 8 (2002).
5. K. Nakagawa, M. de Labachelerie, Y. Awaji, and M. Kourogi, J. Opt. Soc. Am. B **13**, 2708 (1996).
6. K. J. Blow and D. Wood, IEEE J. Quantum Electron. **25**, 2665 (1989).
7. D. Yevick and B. Hermansson, IEEE J. Quantum Electron. **26**, 109 (1990).
8. E. A. Golovchenko, P. V. Mamyshev, A. N. Pilipetskii, and E. M. Dianov, J. Opt. Soc. Am. B **8**, 1626 (1991) and references therein.