Experimental Setup for Electromagnetically Induced Transparency Observation in Hollow-Core Fibers

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ABSTRACT

We developed a system to investigate resonant nonlinear optical interactions in acetylene molecules, confined in a hollow-core photonic crystal fiber (HC-PCF), using light injection through a low-loss splice from one end of the fiber, allowing us to work at low power. Electromagnetically induced transparency (EIT) was observed in the 1500 nm telecommunications window.

Keywords: Electromagnetically induced transparency, hollow-core photonic crystal fiber, telecommunications window, three-level lambda system.

1. INTRODUCTION

Electromagnetically induced transparency (EIT) is a coherent optical effect that provides a narrow spectral transparent window within an absorption medium.[1] In addition, a very sharp variation in dispersion is also created in this transparency window.[2] EIT has attracted considerable interest in recent years, offering a variety of potential practical applications, such as ultra-slow light,[3] all-optical switching[4] and wavelength converters,[5] light storage[6] and single photon switching.[4] Despite the great potential of EIT in Hollow-core photonic crystal fibers (HC-PCF), the development of experimental setups for its characterization is still complex.

The first demonstration of EIT was presented using high power pulsed laser interacting with Strontium vapour,[1] and since then, EIT has been studied in various media, gas vapour cells[7] and lasing without population inversion in an atomic beam.[8] The light propagation can be changed from slow light to fast light regime using EIT,[9] a periodic modulation of atomic absorption can be produced with this phenomenon, inducing a Bragg reflection of the signal.[10]

New possibilities have arisen with the development of HC-PCF, since these fibers can be readily integrated to existing fiber technology, being an ideal bridge between photonics and quantum optics.[11] HC-PCF have the ability to combine light confinement and long interaction length.[11] Efficient Raman scattering at low power regimes was reported in HC-PCF filled with Hydrogen,[12] observation of EIT at 1.5 μm in acetylene-filled HC-PCF, with 70% of transparency,[2] slow light in HC-PCF at telecommunications wavelengths in which a delay of 800 ps was achieved,[11] efficient all-optical switching using slow light,[13] delayed and advanced light pulses in acetylene-filled photonic microcell.[14]

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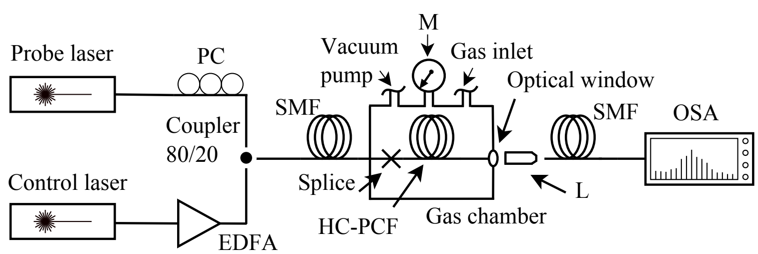
The acetylene (C_2H_2) has been used to investigate optical interactions, due to its spectral overlap with the low-loss fiber telecommunications window.[15] Acetylene is a symmetric molecule which has clean ro-vibrational transitions in this range[16] and besides that, can stay for a long time inside the fiber with no significant leaks, being suitable to build a photonic micro-cell, an excellent tool to implement EIT in telecommunications.

We developed a system to investigate EIT, with an efficient light injection into the HC-PCF, allowing us to work at low powers. This configuration opens the possibility to produce a photonic micro-cell, which is very useful due to its portability, robustness and potentiality to develop all-fiber devices.

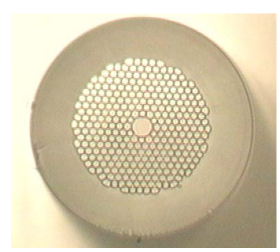
In section II, we present the experimental setup and the procedure used to characterize EIT. In section III, we show the experimental results obtained. The conclusions are presented in section IV.

2. EXPERIMENTAL SETUP

In Fig. 1 (a), we show a schematic diagram of the experimental setup. We used a 1.5 m long HC-PCF (Crystal Fibre, HC-1550-04), which has a core of 10 μm and a mode-field diameter of 9 μm, which makes this HC-PCF very suitable to be low-loss spliced with a standard single-mode fiber (SMF), due to its similar mode-field diameter and core size. It has a bandgap extending over telecommunications window of 1480-1620 nm, holey region of 75 μm and cladding pitch of about 4 μm. One end of the HC-PCF is fusion spliced to a SMF using a Fujikura FSM-60 splicer machine, with a loss of 1.5 dB. The cleaving angle obtained was smaller than 0.5°, which is important to achieve low-loss transition between HC-PCF and SMF in a fusion splice. Besides that, solvents for fiber cleaning were not used, to prevent infiltration into the HC-PCF holes. We used a mechanical stripper and dry wiped to remove remains of the acrylate coating. The splice method is based on joining the fibers in a butt-coupling, obtaining the maximum transmission between the fibers in real time, with the help of a power-meter and a source at 1550 nm, before applying the electric discharge. The losses are determined by measuring the transmitted power before and after fusion. The splicer runs in manual alignment mode, and the electrical discharge is applied over the solid fiber SMF, in order to avoid the collapse of the air holes.[17] To minimize this collapse effect, we choose a weaker fusion current and a shorter fusion time, compared to the ones for splicing standard solid fibers. We used an offset between the joint and the central axis of the arc discharge, applying the less possible amount of heat to the tip of HC-PCF, ensuring the preservation of the hole structure. Using the higher softening point of the SMF, we could produce a resistant splice, optimizing the splicer parameters. In Fig. 1 (b) we show the transverse cross section of the HC-PCF used in the experiments.



(a)



(b)

Figure 1. (a) Schematic diagram of the experimental setup. Two CW lasers, probe and control fields, are coupled to launch the light via SMF spliced to the HC-PCF. The output is aligned through a window with other SMF to be detected. PC: polarization controller; L: lens; Optical window: anti-reflection coated window. (b) Optical microscope image of the HC-PCF cross section.

The fusion splice, through its SMF section, is then hermetically attached to the gas chamber, which is built with stainless steel. The other end of the HC-PCF is just cleaved, with a high precision cleaver and placed inside the chamber on a V-groove, where is aligned with other SMF through an optical window, covered with anti-reflection coating over the entire range of the transmission window of the fiber, from where we could collect the signal after passing the fiber filled with gas, to be analyzed by an Optical Spectrum Analyzer (OSA).

The experimental procedure used to inject gas into the fiber was as it follows. First, we purge the fiber with acetylene and then evacuate to a pressure below 10^{-6} mbar. We fill the chamber with 99.9 % pure acetylene, and detected spectroscopically the presence of gas inside the core of the fiber. All the experiments are performed between 50-100 mbar. The steady state is reached in 2 days. We use two external-cavity lasers, one tuned to 1517.3144 nm, which is our signal field, and the other one is tuned to 1535.3927 nm, which is our pump field, the latter one amplified by an erbium-doped fiber amplifier (EDFA), and the former one passing through a polarizer controller. Both fields are then combined using a fiber coupler 80/20, and launched into the fiber filled with gas, being collected by a collimator in the output to be analysed.

3. EXPERIMENTAL RESULTS

In Figure 2 we show the energy-level scheme for the three-level lambda system. In order to obtain the probe-field absorption profile, the probe beam is tuned to the R(15) line of the acetylene, at 1517.31 nm, corresponding to the transition between level A, represented by $0\Sigma_g^+$(J=15), and C, represented by $\nu_1 + \nu_3\Sigma_u^+$(J=16). The probe-field power is maintained below 200 μW, while its wavelength is scanned over the transition line R(15). Afterwards, to observe the same transition but in transparency regime, we applied a strong control beam of 290 mW, at 1535.39 nm, corresponding to the P(17) line, between levels B, $0\Sigma_g^+$(J=17) and C.

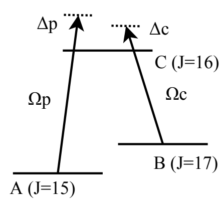
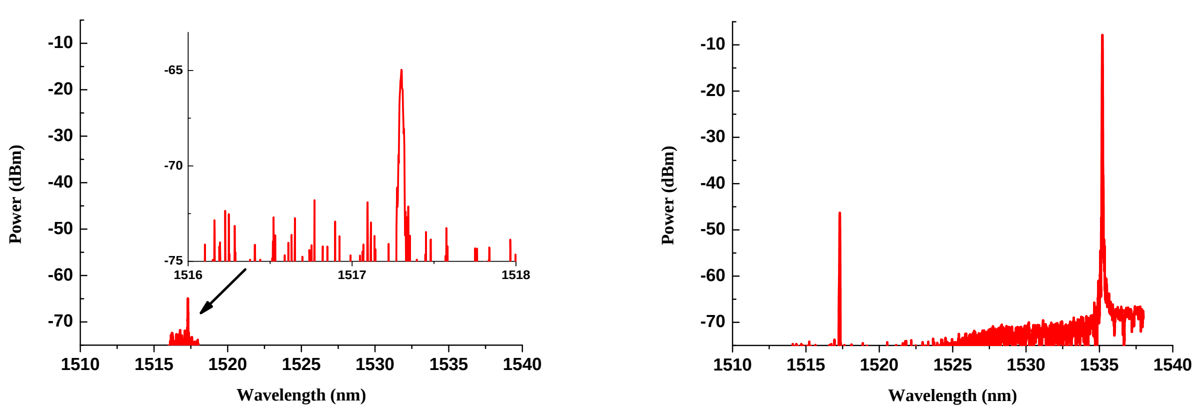


Figure 2. Energy-level scheme for the three-level lambda system. Ω_P and Δ_P are the Rabi frequency and frequency detuning for the probe field, respectively, and Ω_C and Δ_C are the Rabi frequency and frequency detuning for the control field.

In Figure 3 the transmission spectra of the probe-field signal, with and without control field, *i.e.*, the power transmission in function of the wavelength, at the central wavelength of the probe-field signal.



(a) (b)

Figure 3. (a) Transmission spectra of the probe-field signal, at 1517.31 nm, without (a), and with (b) control field, at 1535.39 nm, in function of the wavelength.

Figure 4 shows a typical trace of the probe-field absorption profile, scanned over the R(15) transition line, with and without the control beam. With the control field on, a narrow transparency window is opened at 1517.31 nm, and it is obtained a transparency peak of 24 nW.

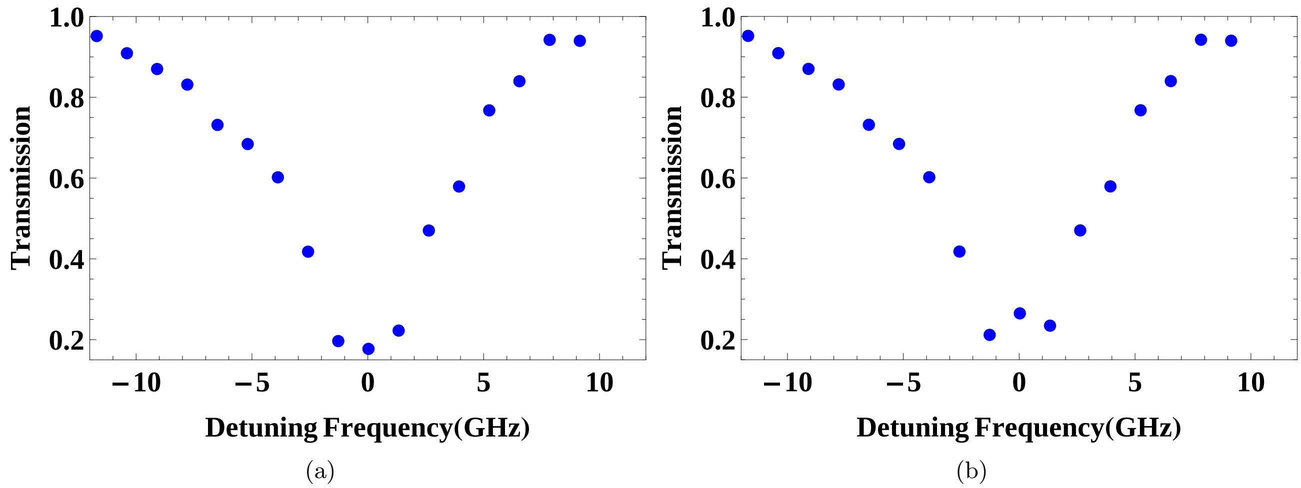


Figure 4. (a) Measured probe-beam absorption profile, scanned over the R(15) transition in acetylene, within a 1.5 m long HC-PCF. (b) Measured profile for the same transition, but in the presence of a strong control beam.

4. CONCLUSIONS

In summary, we have developed an experimental setup to investigate coherent three level interactions, inside an acetylene-filled HC-PCF core. Electromagnetically induced transparency was observed, at low powers, due to its light launching configuration, through a low-loss splice. We obtained the typical trace of the probe-field absorption profile, without a control field and when this is on, where it is achieved a transparency peak of about 24 nW, suitable to apply to low-light applications, such as quantum communications. The width (FWHM) of the obtained transparency window is 800 MHz. In order to increase the transparency peaks, we need to work with lower pressures, to decrease the incoherence sources in the system, such as collisions of the molecules with each other and with the fiber wall, as well as the absorption of the probe-field. This setup will allow enclosure the gas inside the fiber core using a second splice, which will be addressed in our future work.

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REFERENCES

[1] Boller, K.-J., Imamoglu, A., and Harris, S. E., "Observation of electromagnetically induced transparency," *Phys. Rev. Lett.* **66**, 2593–2596 (May 1991).

[2] Benabid, F., Light, P., Couny, F., and Russell, P., "Electromagnetically-induced transparency grid in acetylene-filled hollow-core PCF," *Opt. Express* **13**, 5694–5703 (Jul 2005).

[3] Kash, M. M., Sautenkov, V. A., Zibrov, A. S., Hollberg, L., Welch, G. R., Lukin, M. D., Rostovtsev, Y., Fry, E. S., and Scully, M. O., "Ultraslow group velocity and enhanced nonlinear optical effects in a coherently driven hot atomic gas," *Phys. Rev. Lett.* **82**, 5229–5232 (Jun 1999).

[4] Harris, S. E. and Yamamoto, Y., "Photon switching by quantum interference," *Phys. Rev. Lett.* **81**, 3611–3614 (Oct 1998).

[5] Schmidt, H. and Ram, R. J., "All-optical wavelength converter and switch based on electromagnetically induced transparency," *Applied Physics Letters* **76**(22) (2000).

[6] Phillips, D. F., Fleischhauer, A., Mair, A., Walsworth, R. L., and Lukin, M. D., "Storage of light in atomic vapor," *Phys. Rev. Lett.* **86**, 783–786 (Jan 2001).

[7] Gea-Banacloche, J., Li, Y.-q., Jin, S.-z., and Xiao, M., "Electromagnetically induced transparency in ladder-type inhomogeneously broadened media: Theory and experiment," *Phys. Rev. A* **51**, 576–584 (Jan 1995).

[8] Padmabandu, G. G., Welch, G. R., Shubin, I. N., Fry, E. S., Nikonov, D. E., Lukin, M. D., and Scully, M. O., "Laser oscillation without population inversion in a sodium atomic beam," *Phys. Rev. Lett.* **76**, 2053–2056 (Mar 1996).

[9] Agarwal, G. S., Dey, T. N., and Menon, S., "Knob for changing light propagation from subluminal to superluminal," *Phys. Rev. A* **64**, 053809 (Oct 2001).

[10] Bae, I.-H., Moon, H. S., Kim, M.-K., Lee, L., and Kim, J. B., "Transformation of electromagnetically induced transparency into enhanced absorption with a standing-wave coupling field in an Rb vapor cell," *Opt. Express* **18**, 1389–1397 (Jan 2010).

[11] Ghosh, S., Sharping, J. E., Ouzounov, D. G., and Gaeta, A. L., "Resonant optical interactions with molecules confined in photonic band-gap fibers," *Phys. Rev. Lett.* **94**, 093902 (Mar 2005).

[12] Benabid, F., Knight, J. C., Antonopoulos, G., and Russell, P. S. J., "Stimulated raman scattering in hydrogen-filled hollow-core photonic crystal fiber," *Science* **298**(5592), 399–402 (2002).

[13] Bajcsy, M., Hofferberth, S., Balic, V., Peyronel, T., Hafezi, M., Zibrov, A. S., Vuletic, V., and Lukin, M. D., "Efficient all-optical switching using slow light within a hollow fiber," *Phys. Rev. Lett.* **102**, 203902 (May 2009).

[14] Wheeler, N., Light, P., Couny, F., and Benabid, F., "Slow and superluminal light pulses via eit in a 20-m acetylene-filled photonic microcell," *Lightwave Technology, Journal of* **28**, 870–875 (March 2010).

[15] Swann, W. C. and Gilbert, S. L., "Pressure-induced shift and broadening of 1510–1540-nm acetylene wavelength calibration lines," *J. Opt. Soc. Am. B* **17**, 1263–1270 (Jul 2000).

[16] Keppler, K., Mellau, G., Klee, S., Winnewisser, B., Winnewisser, M., Pliva, J., and Rao, K., "Precision measurements of acetylene spectra at 1.4μm 1.7μm recorded with 352.5-m pathlength," *Journal of Molecular Spectroscopy* **175**(2), 411 – 420 (1996).

[17] Xiao, L., Demokan, M., Jin, W., Wang, Y., and Zhao, C., "Fusion splicing photonic crystal fibers and conventional single-mode fibers: Microhole collapse effect," *Lightwave Technology, Journal of* **25**(11), 3563–3574 (2007).