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# Saturated absorption spectroscopy using azimuthally structured mode in hollow-core fiber

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**Abstract:** We report on transversally structured beam effect on saturated absorption spectroscopy in acetylene-filled hollow-core fiber. Experimental results reveal frequency shift and contrast enhancement of absorption lines using LP<sub>11</sub> guided mode rather than gaussian-like mode. © 2022 The Author(s)

Sub-Doppler spectroscopy such as electromagnetically induced transparency (EIT) or saturated absorption spectroscopy (SAS) is usually performed with a Gaussian mode profile both in free-space and guided optics configurations. Recently, in free space, works have been reported where Laguerre-Gaussian (LG) modes have been set as pump or probe beams in EIT [1–5] and SAS [6] schemes in Rb vapors. Radial variation of LG mode induces narrowing of Doppler-free transparencies profiles. Chanu *et al.* [1] demonstrated decrease of resonances linewidths of Rb of almost factor 6 switching from Gaussian to LG mode. For [5], LG modes contribute to increase the Rb Zeeman level lifetime and so decrease the FWHM. Furthermore, influence of LG modes order has also been studied in [2] demonstrating that larger order induces narrower signal due to its azimuthal component and authors of [4] present the influence of transverse mode overlap (pump and probe) on the signal.

Gas-filled HCPCF technology already demonstrated its potential and impact on the enhancement of the light-gas interactions phenomena and especially in spectroscopy. The various works deriving from the seminal demonstration [7] have been limited to pump (or pump-probe) Gaussian beam configurations due to the fact that most of the developments on HCPCFs have been focused on the design and fabrication of fibers supporting the lowest loss LP<sub>01</sub> like mode with the main objective to increase transmission performances. Moreover, the intrinsic cladding modal properties of microstructured hollow-core fibers render difficult the control on the loss mode hierarchy and to guide light in a high order single mode fashion. This restriction has been lifted by the emergence of the tubular cladding HCPCF providing a large flexibility on the tubes cladding position. Thanks to alteration of the azimuthal position of the cladding tubes, Osorio *et al.* [8] demonstrated, theoretically and experimentally, for the first time in a HCPCF, an inversion of the classical loss hierarchy in fibers developing fibers whose lowest loss modes are the LP<sub>11</sub> and LP<sub>21</sub>, instead of the LP<sub>01</sub>. In this study, we specifically design and fabricate a fiber based on this geometry allowing to guide preferentially high order mode (HOM) around 1550nm without any specific light coupling precaution, we report for the first time to the best of our knowledge on SA spectroscopy generated in HCPCF with a LP<sub>11</sub> high-order mode control beam. Comparison with Gaussian control beam configuration demonstrates an increase of the contrast and peak position shift.

Theoretical approach on saturable absorption process during beam propagation in a gas-filled fiber shows that absorption could be separated in two distinguish expressions. The first one corresponds to the “linear” absorption as observed in usual Doppler limited absorption scheme. The second one, noted  $S_{nm}$ , relates to the saturable part corresponding to the effect of a pump beam and could be expressed as a function of frequency  $\Delta$ :

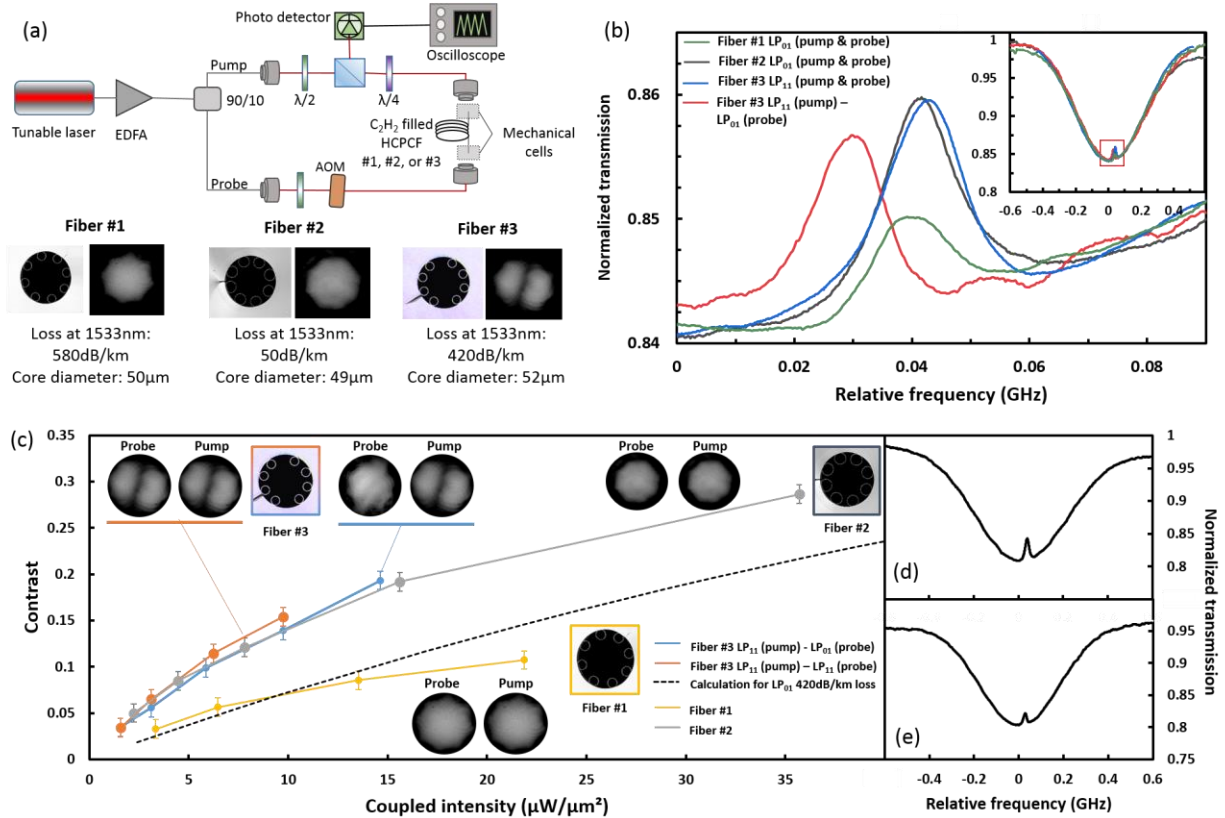
$$S_{nm} = \frac{4(\alpha_f + \alpha_0)E_0^2}{\pi v_0^2} \int_{\bar{r}} \int_{\bar{v}} e^{-\frac{(v_{\theta}^2 + v_z^2)}{v_0^2}} \frac{\Gamma^2 \psi_{nm}(r, \theta)^4}{\left(\Delta + kv_z + \frac{mv_{\theta}}{r}\right)^2 + \Gamma^2} r dr d\theta dv_{\theta} dv_z \quad (1)$$

where  $\Gamma$  is the broadening,  $\alpha_f$  the optical loss of the fiber,  $\alpha_0$  the absorption at resonance  $\Delta=0$ ,  $v_z$  the speed on longitudinal axis,  $v_0$  speed along transversal axis, and  $m$  the mode azimuthal number. By comparing the expression of the saturable part of the absorption for LP<sub>01</sub> and LP<sub>11</sub> mode, one can notice an extra azimuthal term  $\frac{mv_{\theta}}{r}$  that should induce a different Doppler shift.

This effect has been investigated experimentally by comparing SA signals generated with LP<sub>11</sub> and LP<sub>01</sub> control modes inside acetylene filled HCPCFs. For this purpose, we have designed and fabricated three HCPCF (Fig. 1(a)): two tubular lattice fibers with relatively strong 580dB/km LP<sub>01</sub>-loss level for fiber #1, and lower 50dB/km@1530nm loss for fiber #2. Fiber #3 exhibits an asymmetric tubular lattice to guide preferentially LP<sub>11</sub> mode with 420dB/km loss at 1530nm and a core diameter of 52 $\mu$ m. Care has been taken to develop fibers with almost similar core size (~50 $\mu$ m)

and an identical 2.2m length is taken for experiments in order to normalize SA measurements and only consider the influence of HOM. The two first fibers are used as reference and compare to deduce the impact of optical loss on SA signal. The experimental set-up (shown in Fig.1(a)) is similar to a counter-propagative probe-pump scheme in gas-filled fiber. The different fibers have been filled with acetylene at pressure of 0.15mbar. The contrast of Doppler limited absorption profile is measured to ensure that the same gas pressure is set during the three distinct measurement campaigns (with an estimated deviation of less than 0.005mbar). SA measured profiles are presented in Fig. 1(b) for an input intensity of  $6\mu\text{W}/\text{cm}^2$ . One can notice that the peak position is shifted by 10MHz in case of  $\text{LP}_{11}$  mode as pump beam and  $\text{LP}_{01}$  as probe beam in accordance with theory expectation. Finally, Fig. 1(c) shows the contrast evolution with coupled intensity for different probe-pump mode configurations. For same input intensity, and same  $\text{LP}_{01}$  pump and probe modes, fiber #1 with higher loss demonstrates a lower contrast than fiber #2. Fiber #3 with 420dB/km  $\text{LP}_{11}$  loss exhibits higher contrast (for both  $\text{LP}_{11}$  pump- $\text{LP}_{01}$  probe and  $\text{LP}_{11}$  pump- $\text{LP}_{11}$  probe configurations) than the two other fibers despite its higher loss level with contrast enhancement (compared to  $\text{LP}_{01}$  mode with comparable loss level) reaching up to a factor 2. Furthermore, the contrast is also higher than the theoretical calculation for Gaussian mode with 420dB/km loss (dotted curve). These results demonstrate that implementation of  $\text{LP}_{11}$  guided mode profile for SAS allow us to obtain higher contrast with less intensity.

Fig. 1. (a) Setup scheme and description of the used hollow core fibers. (b) SAS measurement at  $6\mu\text{W}/\text{cm}^2$  of input intensity and (c) evolution of contrast with coupled intensity for different probe-pump mode configurations. Measured SA spectrum at  $14\mu\text{W}/\text{cm}^2$  of input intensity for  $\text{LP}_{11}$  probe and pump (d) and  $\text{LP}_{01}$  probe and pump configuration (e).



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