Dynamics of photothermal phase modulation in a gas-filled hollow-core photonic bandgap fiber

Yuechuan Lin[1,2], Wei Jin[1,2], Fan Yang[1,2], and Yang Liu[3]
[1]*Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*
[2]*Photonic Sensors Research Center, The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, 518057, China*
[3]*Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*
e-mail address: lin.yuechuan@connect.polyu.hk

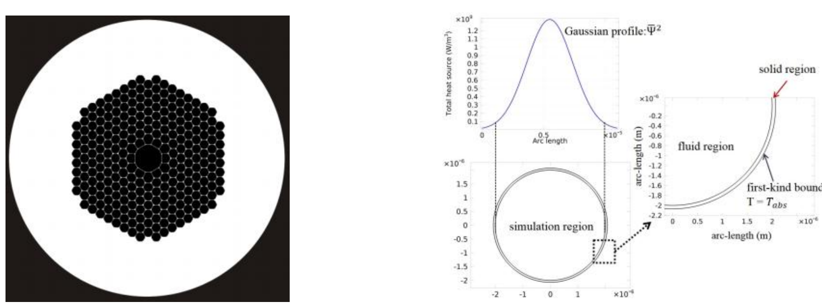
Abstract: The dynamics of photothermal phase modulation in a gas-filled hollow-core photonic bandgap fiber pumped by a pulsed laser is investigated. The magnitude of phase modulation for different parameters of the pump pulses is studied numerically and experimentally.
OCIS codes: (060.2310) Fiber optics; (060.4005) Microstructured fibers; (060.5295) Photonic crystal fibers; (060.2370) Fiber optics sensors; (300.6430) Spectroscopy, photothermal

1. Introduction

Photothermal interferometry (PTI) is an ultra-sensitive spectroscopic method for gas-phase material analysis [1, 2]. Instead of measuring optical spectral attenuation, PTI detects the absorption-induced photothermal (PT) phase modulation. Recently, we studied PTI with a hollow-core photonic bandgap fiber (HC-PBF) and demonstrated detection of acetylene gas down to ppb level with a dynamic range of six orders of magnitude [1]. The use of hollow-core fiber as the sensing platform offers several distinct advantages over free-space approaches. A HC-PBF confines light and gas sample simultaneously within the hollow-core, offering nearly 100% overlap between light and sample gas [3]. The PT phase modulation is proportional to pump light intensity instead of optical power, and for the same pump power level, a HC-PBF could offer a much higher light intensity due to its much smaller mode field area compared with the free-space approaches. Ultra-sensitivity could be achieved by utilizing a longer length of fiber without scarifying compactness since a HC-PBF can be coiled into small diameters with no obvious increase in transmission loss.

Here, we report the results of our theoretical and experimental study of the dynamics of PT modulation in an acetylene-filled HC-PBF using a pulsed pump laser source. Theoretical modeling of temperature distribution within the hollow-core is conducted, the PT phase modulation for different parameters of pump pulses is calculated and compared with experimental results.

2. Theoretical modeling



(a) (b)

Fig. 1. (a) Cross section of the HC-1550-02 HC-PBF from NKT Photonics. (b) Schematic diagram showing the simplified model used in simulation. The simulation region enclosed by the silica tube contains the gas to be measured and the light intensity distribution within this region (for both pump and probe) has an approximate Gaussian intensity profile for the fundamental mode. The temperature of the outer boundary is regarded as a constant and the temperature change is assumed to be continuous at the solid and fluid (gas) interface.

We model the HC-PBF with a simple hollow-tube as shown in Fig. 1. Under the assumption that (1) only the $V \rightarrow R,T$ relaxation process is considered, (2) the gas thermal process within the hollow-core may be approximately regarded the same as in the continuum regime, (3) the thermal conduction is regarded as the dominant heat dissipation process; we may obtained the temperature distribution within the hollow-core by solving the following heat transfer equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (\kappa \nabla \mathrm{T}) + \mathrm{Q} \qquad (1)$$

where $\mathbf{u}$ is the velocity field and $Q(\mathrm{r,t})$ $(\mathrm{W/m^3})$ is the volume heat source. The absorption of the pump beam results in heating around the central portion of the HC-PBF, and the volume heat source $Q(\mathrm{r,t})$ may be regarded as invariant with z under the condition of weak absorption and expressed in the form of:

$$Q(\mathrm{r,t}) = \alpha I_{pump} \exp(-2r^2 / w_p^2) S(\mathrm{t}) \qquad (2)$$

where $I_{pump} = 2P_{pump} / \pi w_p^2$ is the light intensity of pump beam and the pump intensity is assumed to have a Gaussian distribution with a beam radius of w_p and peak power of P_{pump} . *S(t)* is the pulse waveform in the time domain.

For small temperature changes corresponding to weak absorption, the temperature at the outer boundary of the silica ring may be regarded as constant and equal to the ambient, which is the so-called first-kind boundary condition [2]. The temperature distribution in the inner gas region and the silica ring region is regarded as varying continuously, and all the thermal properties of gas molecules are also regarded as not changing considering the very small temperature changes [2]. Under these conditions, Eq. (1) may be solved numerically and temperature variation $\Delta T(\mathrm{r,t})(= \mathrm{T(r,t)} - \mathrm{T}_{abs})$ may be obtained. The refractive index change in the gas region within the hollow-core may be obtained through the Lorentz-Lorentz relation and expressed as [2]:

$$\Delta n = -(\mathrm{n}_0 - 1) \frac{\Delta T(\mathrm{r,t})}{T_{abs}} \qquad (3)$$

In the case studied in this paper, we use a probe beam with a wavelength close to that of the pump, and the pump and the probe beams may then be regarded to have the same Gaussian intensity distribution with the same beam radius w_p . The change of effective refractive index of the propagating probe mode may then be calculated [4] and the overall phase change of the probe beam along a length of L may be obtained by using [5]:

$$\Delta\phi(\mathrm{t}) = -\frac{2\pi L(n_0 - 1)}{\lambda} \int \frac{\Delta T(\mathrm{r,t})}{T_{abs}} \cdot \frac{2}{\pi w_p^2} \exp(-2\mathrm{r}^2 / \mathrm{w}_p^2) \cdot 2\pi\, \mathrm{rdr} \quad (4)$$

where n_0 is the refractive index of gas sample under standard temperature/pressure (s.t.p) condition, for nitrogen $n_0 \approx 1 + 2 \times 10^{-4}$. L is the length of HC-PBFs (in our simulation and experiment L=0.62m), λ is the wavelength of probe beam.

Figure 2(a) shows the results of temperature rise $\Delta T(\mathrm{r,t})(= \mathrm{T(r,t)} - \mathrm{T}_{abs})$ in a 0.62-m-long HC-PBF, containing 100 ppm (parts per million) C_2H_2, with a peak pump power of 25 mW at 1530.371 nm using pulse width of 2 μs at the time of 1.5 μs after pump pulse is on. As expected, the value of ΔT is very small, and the maximum ΔT occurs at the center of the fiber and is less than 0.002 K. The arrows in Fig. 2(b) represents the direction of heat flux, indicating that the heat tends to dissipate outward to reach thermal equilibrium as expected.

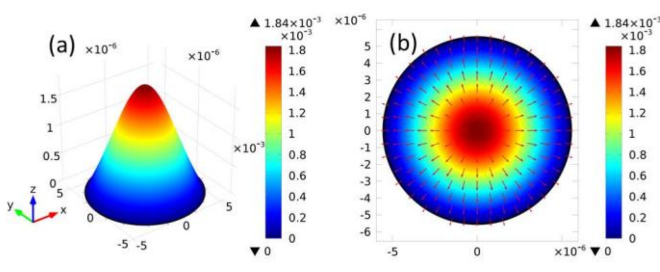
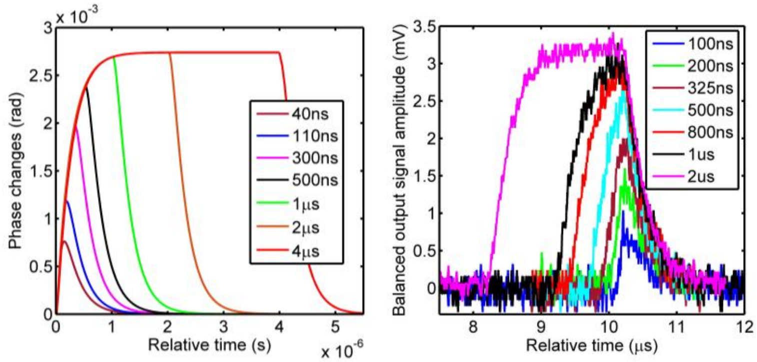


Fig.2. Numerically calculated temperature distribution within a HC-PBF at 1.5 μs after pump pulse is on. The core radius of the HC-PBF is 5.5 μm, the pump beam spot size is 4.03 μm and pump pulse has peak power of 25 mW and a duration of 2 μs. (a) 3D plot of ΔT (r,t); (b) 2D plot of ΔT (r,t) with heat flow direction indicated with arrows. The unit of temperature change is Kelvin.

The phase modulation dynamics for different pulse duration from 40 ns to 4 μs are calculated and shown in Fig. 3(a)



(a) (b)

Fig.3. (a) Simulation and (b) experimental results of the PT-induced phase modulation in HC-PBF for different pulse widths. Peak power of the pump is 25 mW and acetylene concentration of 100 ppm.

3. Experimental results

The PT-induced phase modulation for a 0.62-m-long HC-PBF filled with 100 ppm acetylene with a pump laser tuned to the P(9) absorption line of the acetylene at 1530.371 nm was measured for different pulse durations and shown in Fig. 3(b). During the experiment, a fiber-optic Sagnac interferometer with a 3x3 loop coupler was used to detect the PT-induced phase modulation, the experimental setup, procedures and more results will be reported in future in a more detailed paper.

The maximum phase modulation increases with the pump pulse width when it is smaller than ~1.5 μs, which is mainly determined by the thermal conduction process. When the pulse width is larger than ~1.5 μs, the maximum phase change will not increase anymore with the increase of pulse width. These results agree well with the simulation results shown in Fig. 3(a), and may be used as a guideline to select the optimal pulse width (or modulation frequency for sinusoidally modulated CW) of the pump laser pulses.

4. Conclusion

In conclusion, we studied the dynamics of PT phase modulation in HC-PBF. The heat transfer model applied in free-space is still valid but with different geometry boundary condition. For constant peak power of the pump pulses, the optimal pump duration to achieve maximum phase modulation is found to be ~1.5 μs, determined by the gas thermal conduction process within the hollow core.

5. Acknowledgements

We acknowledge the support of the Hong Kong SAR government through GRF grant PolyU 152064/14E, the National Natural Science Foundation of China (NSFC) through grant No. 61535004.

6. References

[1] W. Jin, Y. Cao, F. Yang, and H. L. Ho, "Ultra-sensitive all-fibre photothermal spectroscopy with large dynamic range," Nat. Commun. **6,** 6767 (2015).

[2] C. C. Davis and S. J. Petuchowski, “Phase fluctuation optical heterodyne spectroscopy of gases,” Appl. Opt. **20,** 2539-2554 (1981).

[3] F. Yang, W. Jin, Y. Cao, H. L. Ho, and Y. Wang, “Towards high sensitivity gas detection with hollow-core photonic bandgap fibers,” Opt. Express **22,** 24894-24907 (2014).

[4] A. W. Synder and J. D. Love, *Optical Waveguide Theory* (Chapman & Hall, 1983).

[5] M. K. Davis, M. Digonnet, and R. H. Pantell, “Thermal effects in doped fibers,” IEEE J. Lightwave Technol. **16,** 1013-1023 (1998).