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Optics Communications 255 (2005) 272–277
OPTICS COMMUNICATIONS
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Gas filled photonic bandgap fibers as wavelength references

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Received 30 March 2005; received in revised form 8 June 2005; accepted 8 June 2005

Abstract

We demonstrate that air-guiding photonic bandgap fibers filled with various gases, such as acetylene and methane provide optical wavelength references. The constructed devices are compact and cost-effective.
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PACS: 33.20.Ea; 42.70.Qs; 42.81.Wg

1. Introduction

Molecular absorption lines are widely used as absolute optical wavelength references for calibration of measurement equipment and frequency stabilization of lasers [1,2]. Absolute wavelength references have been proposed and realized based on gases such as acetylene (C_2H_2), carbon monoxide (CO), hydrogen cyanide (HCN) and methane (CH_4) for the 1300 and 1550 nm regions [3–5]. The gas is typically enclosed in a 5–20 cm long absorption cell. The employed gas pressure depends on the gas species and the cell design. Usually, moderately low pressure (~50 mbar) is desired to avoid the excess pressure broadening and pressure shift of the absorption lines [6]. Thus for weakly absorbing molecules, one might need to increase the interaction length between light and gas to obtain a sufficient signal level. The optical path length can be increased by using a multi-pass configuration but it will usually be limited to around one meter when a portable wavelength calibration device is considered. Therefore, to assure an adequate strength of the absorption lines, a compromise between the pressure and the optical path length is often needed.

The recently emerged air-guiding photonic bandgap fibers (PBFs) provide a means to effectively exploit the interaction of light and gas in a fiber [7,8]. Such fibers do not guide light by total

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doi:10.1016/j.optcom.2005.06.021

internal reflection as in conventional optical fibers but instead make use of the photonic bandgap effect which confines certain light frequencies to the hollow core. In these fibers more than 99% of the light energy can be guided inside the empty core and the nearest neighboring cladding holes [9]. In addition, since PBFs have relatively low bending and transmission loss, they can be coiled on a small-sized spool to realize compact and cost-effective artifacts with a very long optical path length [10–12]. Filling the central voids of a PBF with gas gives a possibility to obtain a large mode-gas overlap and a long optical interaction length at the same time while only a very small quantity of gas is required to fill the core and cladding voids. This allows for the detection of weak absorption lines, which are more difficult to measure using conventional absorption cells due to their limited optical path length.

In this paper, we demonstrate that air-guiding PBFs filled with suitable gases can be used as wavelength references in the 1550 and 1300 nm regions. The fiber samples that are spliced at one end to a single-mode fiber are filled with acetylene or methane and, subsequently, sealed using index-matching adhesive to realize wavelength references. We make use of the concept to stabilize the output frequency of a tunable laser to the center frequency of a weak absorption line of acetylene by using lock-in technique. Moreover, we show for the first time that lines of hot and mixed isotope bands of acetylene can be utilized to accurately reference wavelength-division multiplexing (WDM) channels.

2. Fiber samples

Two different air-guiding PBFs (Crystal Fibre A/S) were employed to realize absolute wavelength references for the telecommunications bands at 1550 and 1310 nm. The wavelength ranges of the photonic bandgap guidance in the fibers are approximately 1250–1380 and 1510–1570 nm, respectively. In both samples, the core was formed by removing seven silica tubes from the center of the preform. The characteristics of the two PBFs labeled PBF1300 and PBF1550 are summarized in Table 1 and the microscope image of the PBF1550 is shown in Fig. 1. The samples are spliced at one end to a standard single-mode fiber terminated by a FC/PC fiber connector to allow for easy light coupling and improved stability. The splice loss was estimated to be ~1 dB for PBF1300 and ~2 dB for PBF1550. The transmission losses for the fiber samples are less than 0.1 and 0.2 dB/m, respectively.

Table 1
Characteristics of the PBFs

	PBF1300	PBF1550
Core size (μm)	11.6	8.5
Length (m)	10	5
Loss (dB/m)	0.1	0.2

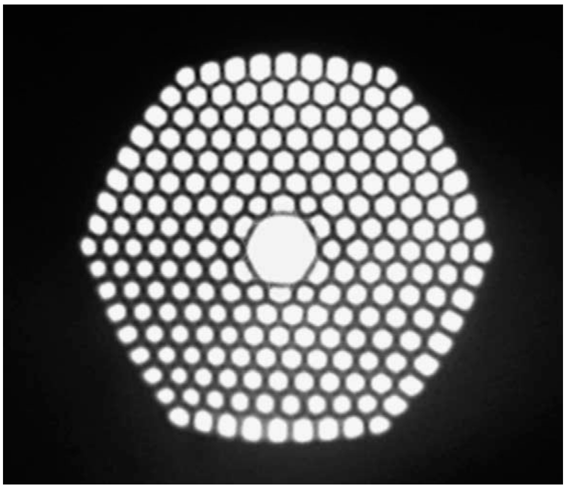

Fig. 1. Microscope image of photonic bandgap fiber guiding around 1550 nm.

3. Molecular references

The absolute wavelength references commonly used are based on the interaction of light and gas in a low-pressure absorption cell. Each gas species has a unique absorption spectrum consisting of absorption bands, and the bands consisting of several absorption lines. Many parameters need to be considered when selecting the gas species to be used for reference purposes: the location and width of the bands, number of absorption lines, strength of lines, pressure, absorption length, availability, hazards, etc. The most utilized and studied reference materials for the near infrared 1300 and 1550 nm bands are acetylene ($^{12}C_2H_2$, $^{13}C_2H_2$) [12–15], carbon monoxide ($^{12}C^{16}O$) [5,16], carbon dioxide ($^{12}C^{16}O_2$) [17], hydrogen cyanide, ($H^{13}C^{14}N$) [16] and methane (CH_4) [5]. The wavelength ranges of the absorption spectra of these gases are presented in Fig. 2.

The WDM channels in fiber-optic communications systems are standardized by the International Telecommunication Union (ITU-T) recommendation [19] to operate at frequencies ranging down from 196 THz with a constant spacing of 100 GHz. The specified maximum wavelength drift from the channel center is 20 GHz. Extensive research has been carried out to find molecular absorption lines that coincide with these channels with an accuracy better than 2 GHz thus being an order of magnitude better than the specified maximum drift. Various acetylene lines and ITU-T channels that nearly coincide are listed in Table 2. The four lines marked with an asterisk have not been suggested, to our knowledge, to be used as WDM channel references. All these lines are located within 1 GHz from the nearest channel.

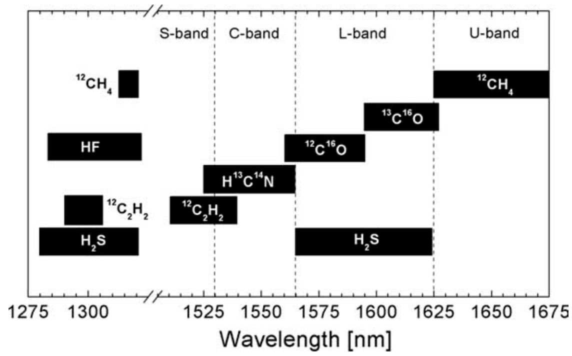

Fig. 2. Most common gas species for referencing the wavelength range used for optical communication [5,16,18].

4. Realization of reference artifact

The experimental setup employed to realize a compact wavelength reference is depicted in Fig. 3. The open end of the PBF was butt-coupled to a multi-mode fiber using a V-groove and was subsequently placed inside a vacuum chamber. The gap between the two fibers was around 100 μm. The fiber was then evacuated using a conventional rotary pump for a time period of minimum 12 h before filling it with either $^{12}C_2H_2$ or $^{12}CH_4$ to the desired pressure. The evacuation times were

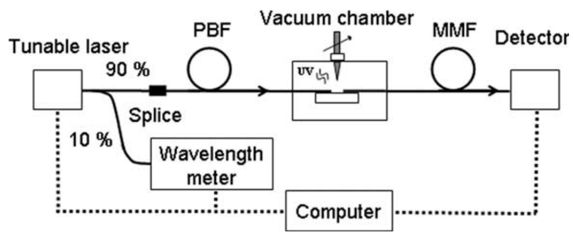

Fig. 3. Measurement setup for realization of reference artifact. Abbreviations: PBF – photonic bandgap fiber; MMF – multi-mode fiber.

Table 2
Absorption lines of C_2H_2 coinciding with ITU-T WDM channels [14]

Line	Molecule	ITU channel	Wavelength (nm)	Frequency (THz)	Difference to ITU channel (MHz)
P(5)[a]	$^{12}C^{13}CH_2$	2	1531.1234	195.79901	−1000
P(14)	$^{12}C_2H_2$	5	1533.4613	195.50051	+500
P(13)[a]	$^{12}C^{13}CH_2$	8	1535.8295	195.19905	−950
P(18)[a]	$^{12}C^{13}CH_2$	12	1538.9689	194.80086	+850
P(17)[b]	$^{13}C_2H_2$	13	1539.7641	194.70025	+250
$P_e(14)$[a]	$^{12}C_2H_2$	13	1539.7623	194.70048	+500
P(13)	$^{13}C_2H_2$	14	1540.5673	194.59874	−1250

Note. The designation *e* is defined within [14].
[a] New candidates for WDM channel references.
[b] $v_1 + v_2 + v_4^1 + v_5^{-1}$ band.

investigated by first filling the fiber with acetylene and subsequently evacuating it while measuring the strength of the absorption line.

A special arrangement was used for sealing of the gas-filled PBF. A thin tube for the application of transparent adhesive and an UV guide were built inside the vacuum chamber. After the fiber had been filled with gas, a small amount of adhesive was injected to the butt coupling. Subsequently, the chamber pressure was rapidly elevated to around 20 mbar to prevent the adhesive from boiling when exposed to UV-radiation. The refractive index of the adhesive (Norland; optical adhesive 61) was estimated to be 1.53 at 1.55 μm. The evaporation pressure at room temperature was found to be ~2 mbar before being exposed to UV-radiation. We observed that the insertion of the index-matching adhesive introduces an additional transmission loss of ~2 dB.

5. Measurement results

The absorption spectrum of the 5-m long PBF1550 filled with C_2H_2 (1.1% natural abundance of ^{13}C) was measured using the experimental setup described in Fig. 3. The fiber was filled to various pressures to measure the different branches of acetylene after it had been pumped empty for a time period of minimum 12 h to effectively evacuate the air holes inside the fiber. The standard $v_1 + v_3$ P-branch was recorded for a pressure of 1 mbar by scanning the wavelength of the tunable laser in wavelength steps of 1 pm. The measured spectrum is presented in Fig. 4. Even at such a low pressure, the absorption lines reached a maximum strength of 16 dB and lines up to P31 are visible.

Encouraged by the high sensitivity of the gas-filled PBFs, we investigate the applicability of weak absorption lines as possible candidates for wavelength references. Increasing the gas pressure to 20 mbar allows study of the $v_1 + v_3 + v_4^1 - v_4^1$ hot band, $v_1 + v_3 + v_5^1 - v_5^1$ hot band, and the $v_1 + v_3$ $^{12}C^{13}CH_2$ mixed isotope bands in detail. In this way, we were able to observe the four lines P(5), P(13), P(18) and $P_e(14)$ given in Table 2. A part of the measured spectrum showing the three

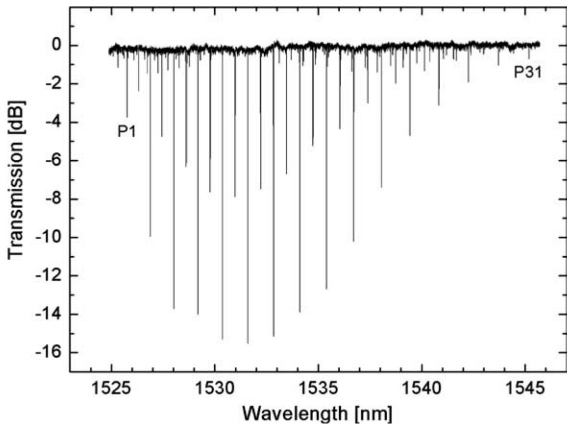

Fig. 4. Absorption spectrum of the P-branch of $^{12}C_2H_2$ measured with a 5 m long PBF filled to 1 mbar with a resolution of 1 pm.

latter lines is presented in Fig. 5. At this pressure, the pressure shift and pressure broadening of the lines are still small being 0.1 and 2 pm at maximum [6] and thus allowing these lines to be used as wavelength references [3] for WDM systems.

Subsequently, we applied the concept to stabilize the output frequency of a commercially available tunable external cavity laser (Nettest Tunics Plus) by locking it to the center point of an absorption line using a lock-in technique. For this purpose, the lines marked in Fig. 5 were chosen. The center

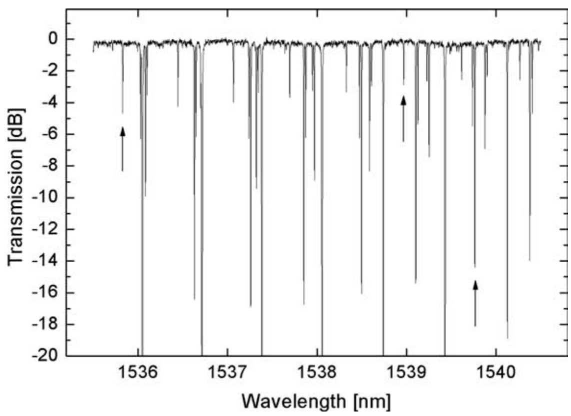

Fig. 5. Absorption spectrum of acetylene in a 5 m long PBF filled to 20 mbar showing the weak bands and the lines coinciding with ITU-T WDM channels 8, 12 and 13. The resolution used was 1 pm.

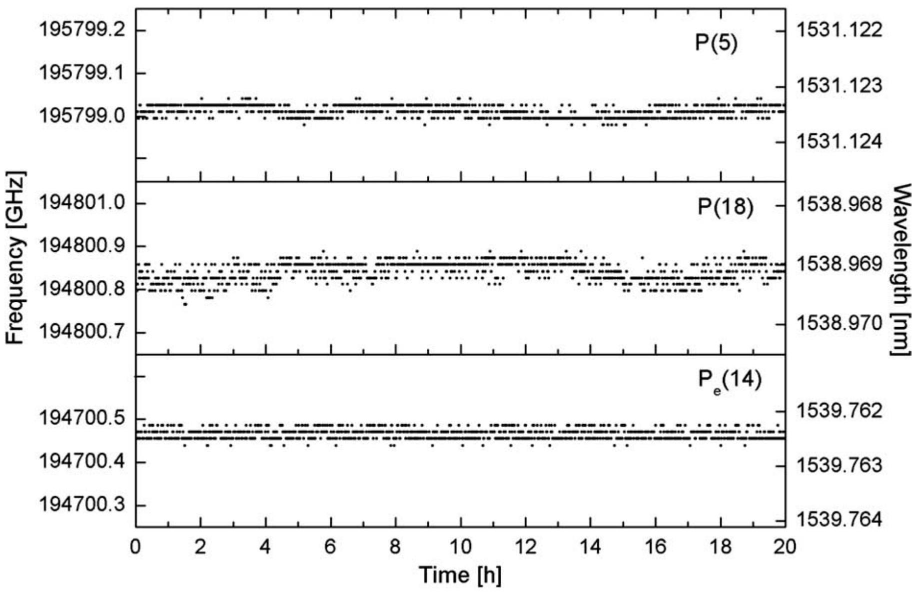

Fig. 6. Frequency stability of laser locked to P(5) of $^{12}C^{13}CH_2$, P(18) of $^{12}C^{13}CH_2$ and $P_e(14)$ of the $\nu_1 + \nu_3 + \nu_4^1 - \nu_4^1$ transition of $^{12}C_2H_2$ lines of acetylene for 20 h.

point of the absorption line is preferred instead of the slope as this makes the absorption line wavelength values straightforward to compare with values found in the literature [13,14]. The measurement results are presented in Fig. 6. The laser frequency stayed within 100 MHz for a time period of 20 h with an integration time of ~100 ms. The performance is sufficient for future dense WDM systems with channel spacing of only 25 GHz. The values were measured with a wavemeter (Burleigh WA-7600) specified to a resolution of 0.1 pm and an accuracy of 0.3 pm.

It appears likely that WDM will be extended to cover the entire useful transmission band of optical fiber. Therefore, to provide a wavelength reference for the 1300 nm region, we filled a 10-m long piece of bandgap fiber guiding in this region with $^{12}CH_4$. Methane has a congested spectrum of weak absorption lines around this region [5]. For referencing purposes, it is important to choose a single line to obtain high accuracy. One particularly suitable single line belonging to the R-branch of the $\nu_2 + 2\nu_3$ combination band near 1314 nm has been recently measured using a heterodyne technique [5]. Since methane is ~100 times weaker absorbing gas than acetylene, a longer fiber was chosen to increase the strength of the absorption lines. With conventional absorption cells, it is cumbersome to achieve such a long path length. The spectrum recorded for a pressure of 900 mbar is shown in Fig. 7. The single line is marked in the figure by an arrow.

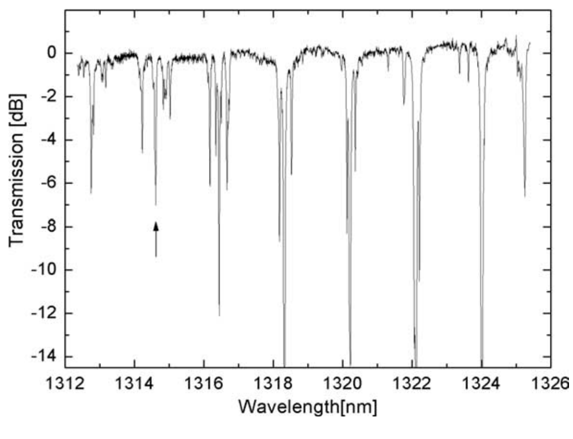

Fig. 7. Absorption spectrum of CH_4 at 900 mbar measured with PBF1300 using a 5 pm resolution.

6. Conclusion

We have demonstrated that PBFs filled with acetylene or methane can provide optical wavelength references for monitoring and calibrating channels in WDM communication systems. With the long natural interaction length of the fiber, weak absorption lines can be used without the need of long multi-pass absorption cells. By using a lock-in technique, the output frequency of a tunable laser was successfully stabilized to three weak absorption lines of acetylene, which coincide nicely with WDM channels.

Acknowledgments

J.T., T.R. and H.L. are grateful to the Academy of Finland. T.R. is also thankful to the Graduate school of Modern Optics and Photonics for financial support.

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