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Humidity Sensor Based on a Photonic Crystal Fiber Interferometer

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A photonic crystal fiber interferometer that operates in reflection mode for humidity detection is presented for the first time which has the advantage that it does not require the use of any hygroscopic material. The fabrication of the sensor head is therefore simple since it only involves cleaving and splicing. The all-silica nature of the device has the potential for many applications.

Introduction: The measurement of humidity is required in a range of areas, including meteorological services, the chemical and food processing industry, civil engineering, air-conditioning, horticulture, and electronic processing. By comparison to their conventional electronic counterparts, optical fiber humidity sensors offer specific advantages, such as small size and weight, immunity to electromagnetic interference, corrosion resistance and remote operation. A wide range of optical fiber humidity sensors have been reported in the literature. Most of these fiber optic humidity sensors work on the basis of a hygroscopic material coated over the optical fiber to modulate the light propagating through the fiber [1]. A polymer optical fiber has been adapted for humidity sensing [2] without the use of a hygroscopic coating but the fiber is highly temperature dependent and is not suitable for high temperature applications. In this letter we present a novel all-glass fiber optic humidity sensor which does not require any special coatings to measure humidity. The sensing element is a stub of photonic crystal fiber (PCF) spliced to a standard single mode fiber (SMF). This forms a reflection type two-mode photonic crystal fiber interferometer (PCFI) whose spectrum exhibits good sensitivity to humidity variations. To the best of our knowledge such a silica optical fiber based sensor which does not require the use of a hygroscopic material is reported for the first time.

Experiment: A PCFI for sensing humidity is fabricated by splicing a stub of PCF (LMA 10, NKT photonics) to a standard optical fiber (SMF-28, Corning) using a conventional splicing machine. The PCF is made of pure silica and has four rings of air holes arranged in a hexagonal pattern. The light guidance mechanism in such a fiber is by means of modified total internal reflection. The dimensions of the LMA-10 PCF simplify alignment and splicing with the SMF-28 with a standard splicing machine and minimise the loss due to MFD mismatch compared to the other PCFs [3]. During splicing the voids of the PCF collapse completely through surface tension within a microscopic region close to the splice point [4]. For the interferometer fabricated in this study the total length of the collapsed region is ~300 μm. After the splicing, the PCF is cleaved using a standard cleaving machine so that the end of the PCF behaves as a mirror. The holes of the PCF are left open to the ambient atmosphere. The operating principle of the PCFI is based on the excitation and recombination of modes occurring in the region of the PCF in which the voids of the PCF are collapsed. The fundamental SMF mode begins to diffract when it enters the collapsed section of the PCF. Because of diffraction the mode broadens allowing the excitation of two core modes in the stub of PCF [4, 5]. The modes propagate through the PCF until they reach the cleaved end from where they are reflected. When the reflected modes re-enter the collapsed region they are recombined as a single SMF core mode.

Fig. 1 shows the setup to interrogate the fabricated PCF interferometer. Light from a broad brand source (BBS), a SLD in this case, is launched into the interferometer through a fiber optic circulator and the reflected light from the cleaved end is fed to an optical spectrum analyser (OSA). This setup allowed for the tracking of the shift of the interference peaks with high resolution. The reflection spectrum of the interferometer exhibits a regular interference pattern where the period of the interference pattern is inversely proportional to the length of the PCF section [4, 5]. The length of the PCF section used is 34 mm and the period of the interference pattern obtained for this length is 10.3 nm. The humidity response of the fabricated PCF interferometer is studied at room temperature and normal atmospheric pressure by placing it in a customised climate chamber which consists of a sealed acrylic chamber with a dry/wet air flow system that can vary the internal humidity. An electronic relative humidity (RH) sensor was used for monitoring the temperature and humidity inside the chamber.

Results and Discussion: We have observed the response of the PCFI for a range of humidity values from 40% RH to 95% RH. It was found that the position of the interference peaks shifted with humidity variations. Fig. 2 illustrates the shifts of a typical interference peak of the reflected light from the PCFI for different ambient relative humidity values. The interference peak shifts to higher wavelengths with an increase in humidity. A similar structure was studied by J Villatoro et al [5] for detecting volatile organic chemical (VOC) vapours and it was shown that the shift is directly related to the refractive index (RI) of the VOC vapour. However the RI of water vapour is almost equal to that of the air and furthermore changes in humidity have a negligible impact on the RI. This suggests that no significant shift should occur with a change in humidity. We attribute the shift of the interference peak to the adsorption and desorption of H_2O molecules along the surface of holes within the PCF, at the interface between air and silica glass. The mechanism of adsorption of water vapour by the surface of silica has been demonstrated in [6, 7]. K. Tiefenthaler et al in [8] have shown that adsorption and desorption of water vapour by the surface of a waveguide changes the effective RI of the guided modes, for the case of a humidity sensor based on an integrated optical grating coupler. In the case of a PCF a similar adsorption and desorption of water vapour on the surface of the silica hole/air interfaces of PCF changes the effective refractive indices of the modes propagating in the PCF.

In [9] it was shown from the adsorption isotherm that the thickness of the adsorbed layer on a hydrophilic silicon oxide surface at room temperature starts increasing exponentially at above 60% RH. The effective RI of the interfering modes changes with respect to the thickness of this adsorbed layer inside the air holes of the micro structured silica fiber. The variation in the effective RI in turn causes a phase change between the interfering modes resulting in a shift of the interference pattern that is a function of ambient relative humidity. The peak wavelength shift of the PCFI is plotted against ambient RH in Fig. 3. In the region from 40 to 70 % RH the PCFI shows a sensitivity of ~ 5.6 pm/%RH. The shift of the interference pattern is most significant above 70% RH in a manner similar to the adsorption isotherm and shows a sensitivity of ~24 pm/%RH. This is much better compared to the reported highest sensitivity for a FBG based relative humidity sensor. The response of the reflection mode PCFI to humidity variations is found to be reversible and repeatable with low hysteresis. Conventional glass fiber relative humidity sensors require coatings and thus are always temperature dependent and furthermore since the majority of such sensors use polymer materials as coatings, they are not suitable for use in high temperature applications. One significant advantage of the sensor proposed here is that the sensor head is made of single material silica. This suggests that apart from low and room temperature applications the PCF interferometer based humidity sensor proposed here can also be used in harsh and high temperature environments to monitor humidity.

Conclusion: A PCFI that operates in reflection mode is presented and its potential application for humidity detection is demonstrated for the first time. The sensor does not require the use of any hygroscopic material. The fabrication of the device is simple since it only involves cleaving and splicing. The interferometer exhibits regular interference patterns which we believe shift due to the adsorption and desorption of H_2O molecules at the air-glass interface within the PCF holes, which is a function of the ambient humidity level. The silica-only nature of the sensor head has the potential for many applications, for example humidity monitoring in high temperature environments.

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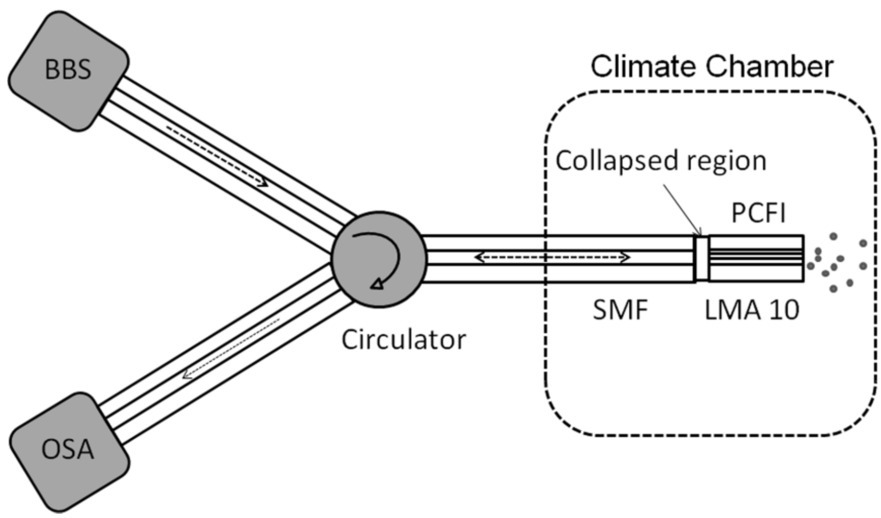
Figure Captions:

Fig. 1 Experimental setup for studies of a photonics crystal fiber interferometer based relative humidity sensor.

Fig. 2 Reflected spectrum of the photonic crystal fiber interferometer for different ambient relative humidity values

Fig. 3 Interference peak shift of the photonic crystal fiber interferometer with respect to relative humidity

Fig. 1



BBS
OSA
Circulator
Climate Chamber
Collapsed region
PCFI
SMF
LMA 10

Fig. 2

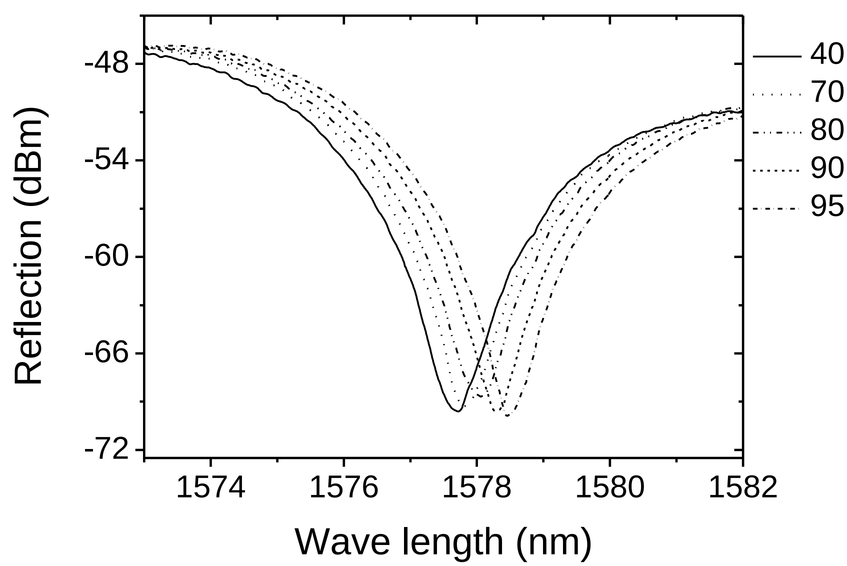
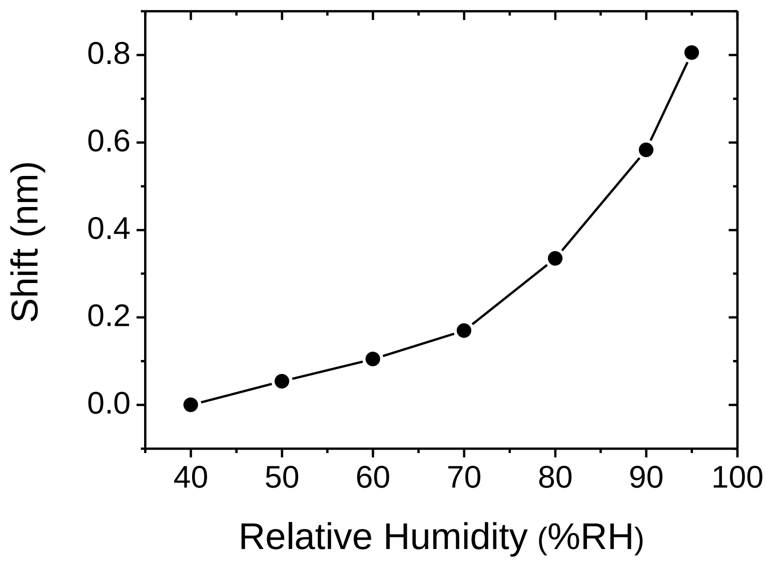

-48
-54
-60
-66
-72
1574
1576
1578
1580
1582
Reflection (dBm)
Wave length (nm)
40
70
80
90
95

Fig. 3



0.8
0.6
0.4
0.2
0.0
Shift (nm)
40
50
60
70
80
90
100
Relative Humidity (%RH)