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Multiplexed long period gratings with differential interrogation

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Abstract. In this work we present experimental results in which we simultaneously detect spectral changes of three long period fiber gratings (LPG) connected in series. The gratings can independently measure surrounding refractive index (SRI) changes $\Delta n$, temperature $T$ and strain $\varepsilon$ in any combination. We have successfully tested them with to simultaneous moisture/evaporation sensing based on SRI change measurements. Such arrangements can be used for simultaneous tracking of hazardous liquid ingress or spill in structural health monitoring applications.

1. Introduction

Long period fiber gratings (LPG) have generated intensive research since their discovery [1] and the most promising applications are related to their high sensitivity to changes in the surrounding refractive index [2]. This allows the development of unique refractometers with applications in chemical and biochemical sensing as well as fiber moisture/evaporation sensors for application in structure health monitoring [3].

We report here the results from experiments with multiplexed LPGs used to monitor wetting and evaporation. Such sensing set-ups can be used to monitor moisture/evaporation of liquids with refractive indices up to 1.41 such as fluorine refrigerant R-22 (1.26), fluorine refrigerant R-12 (1.29), water (1.333), methanol (1.33), propane (1.34), ether (1.35), ethanol (1.36), acetone (1.36), acetic acid (1.37), propyl alcohol (1.38), octane (1.40) and decane (1.41).

2. Long period gratings

A straight unperturbed LPG has a centre wavelength $\lambda_c$ defined as:

$$\lambda_c = \Delta n_{\text{eff}} \Lambda$$  (1)
where $\Delta n_{\text{eff}}$ is the effective core-cladding mode refractive index difference and $\Lambda$ is the pitch of the grating. Strain, temperature and surrounding refractive index (SRI) changes $\delta l$, $\delta T$ and $\delta n$ applied to the grating will induce a shift $\Delta \lambda$ in the centre wavelength accompanied by a decrease of the depth of the transmission notch. The centre wavelength changes are expressed as

$$\Delta \lambda = K_l \delta l + K_T \delta T + K_n \delta n$$

(2)

where $K_i$ ($i = l, T, n$) are the corresponding grating sensitivities depending on the grating parameters.

3. Experimental set-up and results

We studied the spectral shifts of three tapered LPGs manufactured by the arc-fusion method [4]. The gratings were manufactured from an SMF-28 Corning optical fiber using a standard splicer (FITEL S182K). The LPGs were then spliced in series and kept straight.

The gratings were centered correspondingly at 1542 nm, 1581 nm 1626.6 nm and thus the separation between them is 38 nm and 45.6 nm non wetted.

The measurement experimental set-up is shown in figure. 1.

![Figure 1](image)

**Figure 1.** Experimental set-up using a broad-band source (BBS from 1250nm to 1650 nm) and an optical spectrum analyzer (OSA) in combination with three LPGs.

The sensing gratings were placed on supports and covered with a Kimwipe paper blanket which is a porous tissue to help keep the liquid used to wet the LPGs. When an LPG is wetted the SRI changed from that of air $n_a$ to $n_0$. If we denote the surfaces on the fiber grating exposed to air and to the liquid by $s_a$ and $s_0$, then the effective refractive index sensed by the grating is:

$$n = \frac{s_a n_a + s_0 n_0}{s_a + s_0}$$

(3)

During evaporation, the surfaces $s_a$ and $s_0$ change and correspondingly the effective refractive index changes with time. At the initial moment when the LPGs are dry, the spectral distribution $P_0(\lambda)$ is taken as a reference. On wetting the gratings with different liquids such as water, ethanol and acetone, the corresponding spectral distribution $P(\lambda)$ would be measured. In the case of logarithmic units, the optical power $P$ is measured in dBm, defined as $I = 10\log[P/1\text{mW}]$ as shown in figure 2. We then calculate the differences for each wavelength of the spectrum

$$\Delta I_i = I(\lambda_i, n) - I(\lambda_i, n_0) = 10\log \frac{P(\lambda_i, n)}{P(\lambda_i, n_0)}$$

(4)

which are shown in figure 3. Next the differences are summed over two spectral intervals $\Delta \lambda_1$ and $\Delta \lambda_2$ as shown by the shado areas in figure 2:

$$I_1 = \sum_{\Delta \lambda_1} \Delta I_i \quad \quad I_2 = \sum_{\Delta \lambda_2} \Delta I_i$$

Finally we calculate the differences between these
\[
\Delta I_{12} = I_1 - I_2 = \sum_{\Delta \lambda_1} 10 \log \frac{P(\lambda_1, n)}{P(\lambda_1, n_0)} - \sum_{\Delta \lambda_2} 10 \log \frac{P(\lambda_2, n)}{P(\lambda_2, n_0)}
\]  (5)

for each separate measurement at a given \( n \). Thus measuring the spectral shape of \( \Delta I_{12} \) it is possible to detect small centre wavelength changes of the LPG caused by external perturbations such as the SRI \( n \).

The final result is shown in figure 4 representing the time dependence of \( \Delta I_{12} \) which is proportional to the degree of wetting of the particular LPG. The spectrally integrated differential loss reaches a maximum when the grating is fully wetted and reduces to zero when completely dry. In our experiments we added drops of liquids and measured the wetting/evaporation responses in time. Since ethanol and acetone have lower specific heats of evaporation they vaporize faster and we have added two drops twice at different moments. The cross-channel noise was estimated to be less than 1.5 %.

![Figure 2](image2.png)
**Figure 2.** Spectral dependencies of the losses for the three sensing LPGs S1, S2 and S3 at different moments of evaporation. The spectral shifts are clearly visible for all gratings.

![Figure 3](image3.png)
**Figure 3.** Spectral dependencies of the relative losses \( \Delta I \) from eq. 4
4. Conclusion
We have observed the time responses of the evaporation process of ethanol, acetone and water from three spectrally multiplexed LPGs. The interrogation method used is based on differential loss measurement with a reference to the spectral distribution at the initial moment. The differential losses are summed over spectral intervals $D_{l1}$ and $D_{l2}$ around the center wavelength of each LPG which allows an easier to implement and cheaper detection system using either separate photodetectors or an InGaAs CCD array [5].

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References

Figure 4. Integrated differential loss which is a measure of the center wavelength shifts of each grating during wetting/evaporation