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Distributed feedback fibre laser sensor for simultaneous strain and temperature measurements in the RF domain

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ABSTRACT

For the first time the RF beat frequencies between two longitudinal modes and two polarisation modes of a birefringent Moiré DFB fibre laser are employed to measure strain and temperature simultaneously. The sensor accuracy was $\pm 25\mu\epsilon$ and ±0.7°C.

1. INTRODUCTION

Measuring strain and temperature simultaneously with fibre Bragg grating sensors, i.e. without cross-sensitivity, is of great importance in many applications. Several techniques have been demonstrated to separate the strain and temperature responses of these sensors. These include employing two independent sensors,[1] two superimposed gratings at widely separated wavelengths,[2] and polarimetric sensors based on birefringent gratings.[3] The increased complexity of the packaging and positioning in the first case and the need for two independent light sources in the second case make these two approaches less practical than polarimetric grating sensors. However, the accuracy of wavelength encoded polarimetric sensors is insufficient for many applications due to the small difference between the strain and temperature dependences of the wavelengths of the two polarisation modes.

In a previous experiment a birefringent distributed feedback (DFB) fibre laser operating stably in two polarisation modes has been employed as a polarimetric sensor for simultaneous strain and temperature measurements.[4] The absolute wavelength of one polarisation mode and the RF beat signal between the two polarisation modes provided the necessary parameters to determine strain and temperature simultaneously. A high measurement accuracy was achieved as a result of the large signal-to-noise ratio, the narrow linewidth of the laser, and the large difference between the wavelength and beat frequency responses. However, a disadvantage of that sensor was the need for two separate interrogation systems for wavelength and RF frequency measurements.

In this paper we report, for the first time, on a polarimetric dual longitudinal mode DFB fibre laser sensor for simultaneous strain and temperature measurements. The sensor operates entirely in the RF domain, thus reducing interrogation system complexity and cost.

2. THEORY

A dual longitudinal mode DFB fibre laser can be regarded as a superposition of two DFB structures lasing in two longitudinal modes with different wavelengths. The wavelengths of the two longitudinal modes vary with strain ϵ and temperature T according to the well known equation

$$\lambda_{m,p}(\epsilon,T)=\lambda^0_{m,p}+\lambda^0_{m,p}(1+p_e)\epsilon\Big|_{T=\mathrm{const}}+\lambda^0_{m,p}(\alpha+\xi)\Delta T\Big|_{\epsilon=\mathrm{const}}\qquad m=1,2,\ p=x,y, \qquad (1)$$

where $\lambda^0_{m,p}$ is the wavelength at $\epsilon = 0$ and $T_0 = 0°\mathrm{C}$, p_e is the strain-optic coefficient, α is the linear thermal expansion coefficient, ξ is the thermo-optic coefficient and $\Delta T = T - T_0$. For the particular Er:Yb-doped fibre $p_e = -0.26$, $\alpha = 0.5\times10^{-6}\,\mathrm{K}^{-1}$, and $\xi = 4.6\times10^{-6}\,\mathrm{K}^{-1}$.[4] Because of the wavelength dependence of p_e and ξ, the strain and temperature responses of the two longitudinal modes differ slightly.[2] This effect can also be detected in the RF domain if the wavelength separation of the two longitudinal modes is $\sim 0.1\,\text{nm}$ at a centre wavelength of $\sim 1550\,\text{nm}$. The longitudinal mode beat frequency between the two x-polarised modes is

$$\nu_x = c/\lambda_{1,x} - c/\lambda_{2,x} \approx c(\lambda_{2,x} - \lambda_{1,x})/(\lambda^0_{1,x}\,\lambda^0_{2,x}), \tag{2}$$

where the denominator has been simplified by neglecting all terms which are small compared to $\lambda^0_{1,x}\cdot\lambda^0_{2,x}$. A similar equation applies to ν_y in the y-polarisation. Because the birefringence of the DFB laser is small $\nu_x(\epsilon,T) \approx \nu_y(\epsilon,T)$ which would make the sensor very sensitive to measurement errors. However, the RF beat frequency between two polarisation modes of the DFB fibre laser, which is independent of the longitudinal beat frequency, is a linear function of strain and temperature[4] and can therefore provide the necessary second parameter to measure strain and temperature simultaneously. The polarisation beat frequency can be expressed as[4]

$$\nu_m(\epsilon,T) = \nu^0_m + \nu^0_m\left[\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}\epsilon} - (1+2p_e)\right]\epsilon\,\Big|_{T=\text{const}} + \nu^0_m\left[\frac{1}{B}\frac{\mathrm{d}B}{\mathrm{d}T} - (\alpha+2\xi)\right]\Delta T\,\Big|_{\epsilon=\text{const}}, \qquad m=1,2. \tag{3}$$

Here $B = n_x - n_y$ is the birefringence of the DFB fibre laser.

The exact strain and temperature responses of the four intermodal beat frequencies are the result of the interplay between the variations of the grating period, the refractive indices at the two wavelengths, and the birefringence of the fibre.

3. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Fig. 1. The 50 mm long Moiré grating structure of the DFB fibre laser was written in uncoated photosensitive Er^{3+}:Yb^{3+}-doped fibre[5] by means of a multiple exposure technique.[6] The wavelength separation between the two longitudinal laser modes was $\approx 0.12\,\text{nm}$, corresponding to a frequency separation of $\approx 14.9\,\text{GHz}$ at a centre wavelength of 1551 nm. The polarisation beat frequency of the longitudinal mode at λ_1 was $\approx 650\,\text{MHz}$. The mode structure of the DFB laser is shown in Fig. 2. Standard telecommunication fibre was spliced to both sides of the laser, approximately 5 mm away from the grating ends. Strain and temperature of the DFB fibre laser were controlled with a manual translation stage and a Peltier element.[4]

The DFB fibre laser was pumped with a 1480 nm semiconductor diode laser. The lasing thresholds were 20 mW and 65 mW for λ_1 and λ_2, respectively. For 80 mW pump power the output power of the DFB fibre laser was $150\,\mu\text{W}$ and $25\,\mu\text{W}$ at λ_1 and λ_2, respectively. Small imperfections of the $\pi/2$-phase shifts of the two longitudinal modes, gain competition, and spatial holeburning are possible explanations for the different thresholds and output powers of the two longitudinal modes. The longitudinal and polarisation beat frequencies of the DFB fibre laser were detected with two separate photodetectors.

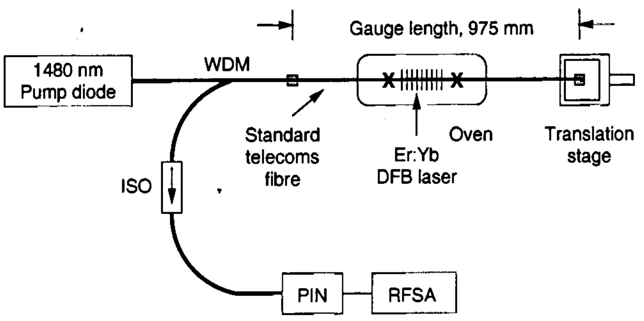

Figure 1. Experimental arrangement, WDM=wavelength division multiplexer, ISO=isolator, PC=polarisation controller, PIN=photodetectors, RFSA=RF spectrum analyser.

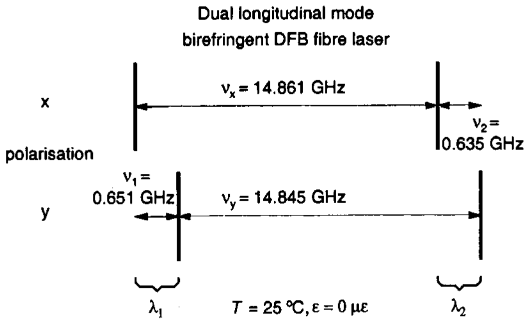

Figure 2. Mode structure of the birefringent Moiré DFB fibre laser and RF beat frequencies between the modes.

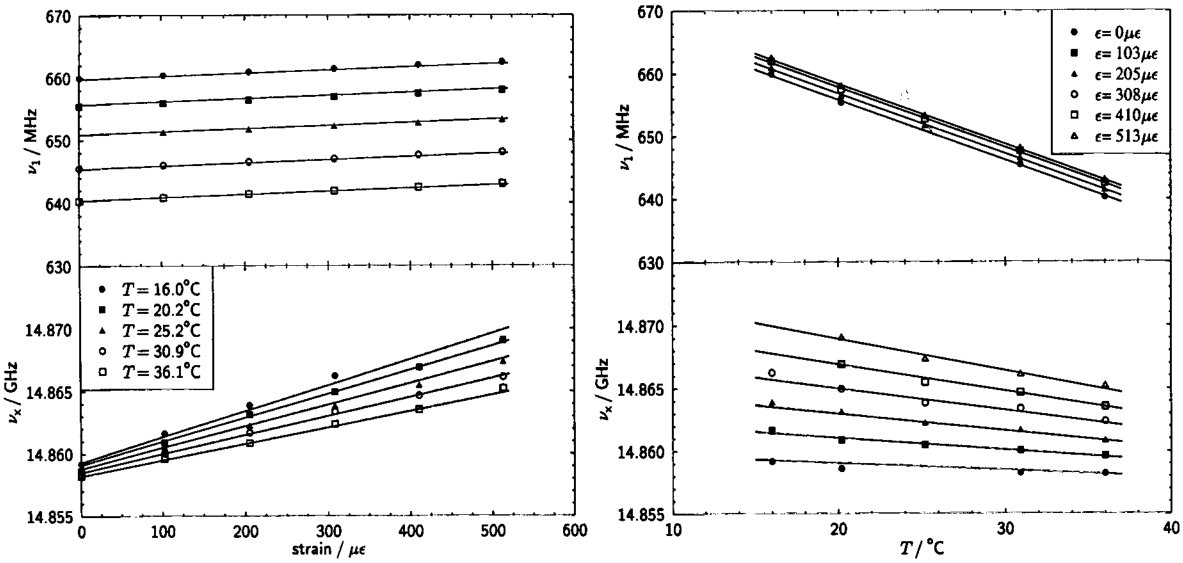

Figure 3. Polarisation and longitudinal beat frequencies as a function of strain (left) and temperature (right). Lines represent best fits, including strain-temperature cross-talk of the longitudinal beat frequency. In the top right graph only four strain levels are shown for clarity.

4. RESULTS

The sensor was calibrated by measuring ν_1 and ν_x at five different temperatures with six strain levels each. The accuracies of the measurements were $\sigma(\nu_x) \approx \pm 30\,\mathrm{kHz}$ and $\sigma(\nu_1) \approx \pm 10\,\mathrm{kHz}$, respectively, limited by the small fluctuations of the beat frequencies. The results are shown in Fig. 3. Both beat frequencies increased linearly with strain and decreased linearly with temperature. While the strain and temperature responses of ν_1 were independent of each other, ν_x exhibits a significant amount of cross-talk, i.e. the strain response depended on the fibre temperature and vice versa (see bottom graphs of Fig. 3). Including the previously omitted strain and temperature dependent terms in the denominator of (2) could not describe this cross-talk. A likely explanation for the cross-talk could be a small temperature dependence of the strain-optic coefficient $p_e(T) = -0.5n(T)^2[p_{12} - \mu(p_{11} + p_{12})]$, where p_{11} and p_{12} are the photo-elastic coefficients, μ is the Poisson ratio of the fibre, $n(T) = n_0(1+\xi T)$ and n_0 is the refractive index at $T = 0$°C. Consequently a term $\propto \epsilon\Delta T$ has to be added to (1). The strain and temperature responses of the polarisation and longitudinal beat frequencies can then be combined in the following matrix form:

$$\begin{pmatrix} \Delta\nu_1 \\ \Delta\nu_x \end{pmatrix} = \begin{pmatrix} k_{11} & k_{12} & 0 \\ k_{21} & k_{22} & k_{23} \end{pmatrix} \begin{pmatrix} \epsilon \\ \Delta T \\ \epsilon\Delta T \end{pmatrix} = \boldsymbol{K} \begin{pmatrix} \epsilon \\ \Delta T \\ \epsilon\Delta T \end{pmatrix}. \qquad (4)$$

$\boldsymbol{K}$ was determined by fitting (4) to the experimental data, resulting in

$$\begin{aligned} k_{11} &= (5.0 \pm 0.2)\,\mathrm{kHz}/\mu\epsilon, \\ k_{12} &= (-0.966 \pm 0.005)\,\mathrm{MHz}/^\circ\mathrm{C}, \\ k_{21} &= (27 \pm 1)\,\mathrm{kHz}/\mu\epsilon, \\ k_{22} &= -(56 \pm 12)\,\mathrm{kHz}/^\circ\mathrm{C}, \\ k_{23} &= (0.38 \pm 0.04)\,\mathrm{kHz}/(\mu\epsilon\,^\circ\mathrm{C}). \end{aligned}$$

Because $\boldsymbol{K}$ is not square solving (4) for ϵ and T yields two pairs of (ϵ, T), of which only one is physically meaningful. It should be noted here that despite the strain-temperature cross-talk of ν_x, both measurands can be determined simultaneously, i.e. the cross-sensitivity of the grating sensor is eliminated.

In order to determine the accuracy of this sensor, the calibration errors and the accuracies of the frequency measurements were added in quadrature. The accuracy of this strain and temperature sensor was calculated to be $\pm 25\,\mu\epsilon$ and ±0.7°C. This accuracy is an order of magnitude worse than the one demonstrated previously for a single longitudinal mode polarimetric DFB fibre laser sensor.[4] The previously mentioned small imperfections of the $\pi/2$-phase shifts, spatial holeburning, and gain competition could result in small optical frequency shifts. Although these effects are thought to be negligible on the scale of the optical frequencies at $\approx 193\,\mathrm{THz}$, small frequency variations of the laser modes in the order of kHz lead to considerable measurement errors.

5. CONCLUSION

In conclusion, we have demonstrated a polarimetric DFB fibre laser sensor for simultaneous strain and temperature measurements which operates entirely in the RF domain. A variety of low cost and precise RF detection schemes could potentially be used with this sensor. The achieved accuracy for simultaneous strain and temperature measurements was $\pm 25\,\mu\epsilon$ and ±0.7°C respectively. Reducing gain competition, spatial holeburning, and grating imperfections are potential routes to improve the accuracy of this sensor. The sensor responded linearly to strain and temperature but a cross-talk between the two measurands was observed.

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