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Novel frequency-agile interrogating system for fibre Bragg grating sensors

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ABSTRACT

We have demonstrated a new frequency-agile system for the interrogation of in-fibre Bragg grating sensors. The scheme involves frequency shift keying (FSK) of the RF drive to an acousto-optic tunable filter (AOTF) to track the wavelength shifts of a Bragg grating. Theoretical studies to derive the optimum frequency deviation for achieving maximum sensitivity are given, and experimental results are presented for temperature measurement. This technique is capable of rapid, random access and very wide tuning range, showing the potential for interrogating multiplexed arrays of Bragg-grating-based sensors.

1. INTRODUCTION

Fibre optic Bragg grating sensors are attracting considerable interest for a number of sensing applications[1-9] because of their intrinsic and wavelength-encoded operation. There is great interest in the multiplexed sensing of smart structures and materials, particularly for real-time evaluation of physical measurands (eg. temperature, strain) at critical monitoring points. In order to interrogate and demultiplex a number of in-fibre Bragg grating sensors, whether they are in a common fibre path or not, it is necessary that the instantaneous central wavelength of each sensor can be identified.

Various schemes to detect small peak wavelength shifts of the gratings have been developed.[5-9] These include the edge-filter demodulation method[5] where a sharp edge of a filter is used to convert wavelength changes to amplitude variations, interferometric-based approaches,[6-7] the use of frequency-locked grating pairs[8] and laser-sensor concepts where the sensor determines the lasing frequency.[4,9]

However, all the above methods have limitations when it is desired to interrogate the wavelength of a large number of fibre-gratings in a frequency-agile manner. In this paper we present a new method of constructing an interrogating system for in-fibre Bragg grating sensors using an acousto-optic tunable filter. This type of filter possesses the desired frequency-agile capability for random access and has a wide tuning range.[10] At constant temperature, its peak transmission wavelength is determined solely by the frequency of an RF drive signal and it is therefore suitable for both dynamic and quasi-static strain sensing in multiplexed sensing systems. In addition, the same detection system can be used to measure the Bragg wavelengths of the gratings in either a reflective or transmissive configuration.

2. PRINCIPLE

Our experimental system is shown schematically in Fig.1. Light from a broadband optical source (ELED) is coupled, via the in-fibre grating to be measured, through the AOTF and then to a detector. The operating principle of the transmission type of an AOTF is described in detail elsewhere.[10] As already mentioned, the wavelength of the light transmitted by the AOTF is a function of the RF frequency. In order to track the Bragg grating, it is feasible to employ a feedback signal to lock the mean optical wavelength of the filter to the instantaneous Bragg wavelength of the in-fibre grating. This involves dithering the applied RF frequency about a nominal value (ie. FSK) and detecting the amplitude modulation of the received optical carrier. Assuming that the AOTF mean wavelength is proportional to the applied RF frequency over the measurand-induced wavelength shift of each in-fibre grating, then for symmetrical grating and filter responses, the amplitude modulation at the dither frequency is zero when the mean wavelength of the AOTF coincides with the Bragg wavelength of the grating. This condition can be achieved by adjusting the mean frequency of the FSK signal.

For given grating and AOTF bandwidths, the optimum frequency deviation can be derived to obtain the maximum error signal for tracking control. We shall initially consider a single grating sensor. We have assumed a Gaussian approximation for the power spectrum of both the grating and the AOTF. The light transmitted, via a in-fibre grating, is then given by:

$$G(f) = 1 - R_G e^{-4\ln2 \frac{(f-f_G)^2}{B_G^2}} \quad \textbf{(1)}$$

where R_G is the reflectivity of Bragg grating, f_G is the Bragg frequency, and B_G is the bandwidth of the grating. We also model the AOTF spectrum with the Gaussian function:

$$F(f) = A_F e^{-4\ln2 \frac{(f-f_F)^2}{B_F^2}} \quad \textbf{(2)}$$

with A_F being a constant determined by transmission loss in the system. Here f_F and B_F are the

AOTF central frequency and FWHM bandwidth, respectively. **Assuming that spectrum of the source is constant within the tuning range**, the intensity at the detector is then proportional to:

$$I=\int_{-\infty}^{\infty}F(f)G(f)df=\frac{A_F B_F\sqrt{\pi}}{\sqrt{4\ln 2}}\left(1-\frac{B_G R_G}{\sqrt{B_G^2+B_F^2}}e^{-4\ln 2\frac{(f_F-f_G)^2}{B_F^2+B_G^2}}\right) \quad \textbf{(3)}$$

When an FSK signal is applied to the AOTF, the amplitude modulation (AM) signal is given by:

$$a_m=I(x+\Delta f)-I(x-\Delta f) \quad \textbf{(4)}$$

where Δf is the frequency deviation of the optical filter as a result of the FSK drive, and $x=f_F-f_G$. Then the maximum tracking sensitivity occurs when:

$$\frac{d}{d(\Delta f)}\left(\left.\frac{d(a_m)}{dx}\right|_{x=0}\right)=0 \quad \textbf{(5)}$$

The optimum frequency deviation is then given by:

$$\Delta f_{opt}=\sqrt{\frac{B_F^2+B_G^2}{8\,ln2}} \quad \textbf{(6)}$$

It should be noted that this only depends on B_F and B_G (ie. it is independent of the filter transmission, grating reflectivity, etc.). Fig.2 shows the AM signal versus the normalized frequency mismatch for three different normalized frequency deviations. The solid line gives the optimum frequency deviation, which, in turn, gives the maximum tracking sensitivity under match conditions.

The FSK signal is conveniently generated using a voltage controlled oscillator (VCO), having a low-frequency square wave added to a DC bias signal, provided to tune the mean frequency. The electronics system shown in Fig.1 should serve to lock the mean frequency of the AOTF to the condition where the amplitude modulation is zero. The mean frequency of the VCO would then provide an indication of the corresponding instantaneous Bragg wavelength of the sensor. *For multiplexing, it would, of course, be necessaryto apply an impulse to the VCO input to cause it to address and then lock onto a different in-fibre grating. Alternatively the filter could be simultaneouslydriven by multiple RF signals of differentfrequencies, each set to track* *a particular grating, as described above.*

3. EXPERIMENT AND DISCUSSION

In our experimental demonstration, we have shown the basic concept to be feasible by operating the system in open loop configuration. The broadband source used was a 1300 nm single-mode fibre-pigtailed ELED, which launched ~50 μW of output power over a ~56 nm bandwidth (FWHM). The sensing grating, having a nominal (ie. unstrained and at room temperature) Bragg wavelength of ~1298 nm, a peak reflectivity of 99% and a bandwidth of ~1 nm (FWHM), was incorporated between the optical source and the AOTF. The AOTF (Crystal Technology, MID-IR AOTF) had a wavelength tuning range of 1.2 μm-2.5 μm and a resolution (FWHM) of 4 nm. We used a commercial RF signal generator (MARCONI 2031) as a VCO. The frequency deviation of the FSK-modulated drive signal to the AOTF was chosen to be 360 KHz to obtain optimum sensitivity for the particular AOTF/grating configuration. The mean RF drive frequency was manually chosen to be 111.58 MHz, to set the mean AOTF wavelength to the nominal Bragg wavelength.

Fig.3 shows the system output from the optical detector, with the modulation-input frequency to the VCO set to 200 Hz, and with the mean RF frequency detuned from the matching condition. The modulation signal at the detector becomes zero only when the mean AOTF wavelength matches the instantaneous Bragg-grating wavelength. For the purpose of our initial feasibility experiment we have chosen to measure temperature using the grating. The temperature measurement results shown in Fig.4 were obtained by heating the Bragg grating using a Peltier heat pump. The thermal sensitivity of the Bragg grating was measured to be -0.95 KHz/°C, in terms of RF frequency shifts, a value in close agreement with the value expected.[3] Clearly, similar results are expected if the in-fibre grating were to be stretched (-0.098 KHz/με[1]) or pressurised (0.26 KHz/MPa[3]), provided the same AOTF is used at same wavelength.

4. CONCLUSIONS

We have demonstrated an attractive method for the interrogation of a Bragg grating sensor using an acousto-optic tunable filter. Although, in our first experiment, this was for thermal monitoring, strain or pressure measurement should equally be possible. This technique offers considerable advantage over previous approaches. In particular the method has the potential for frequency-agile access, wide tuning range, and the ability to recover after transient signal loss, etc., all of which are likely required in practical multiplexing applications. The system developed is therefore likely to provide a practical means for interrogating multiplexed in-fibre

Bragg grating sensors.

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