New Multiplexing Scheme for Monitoring Fiber Optic Bragg Grating Sensors in the Coherence Domain

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Abstract

A new multiplexing scheme for monitoring fiber optic Bragg gratings in the coherence domain has been developed. Grating pairs with different grating distances are distributed along a fiber line, and interference between their reflections is monitored with a scanning Michelson interferometer. The Bragg wavelength of the individual sensor elements is determined from the interference signal frequency.

Introduction

Many methods have been devised for interrogating in-fiber Bragg gratings, including scanned filters (e.g., Fabry-Perot [1], acousto-optic [2], and stretched-fiber grating [3]), passive filters using wavelength selective couplers [4], readout spectrometers [5,6] and stretched-fiber interferometers [7]. The passive wavelength-selective filters and the acousto-optic tunable filters have the potential for fastest response, but the stretched fiber interferometer has, so far, demonstrated the greatest wavelength measurement precision. The latter can also be used in principle to read multiple arrays of gratings using Fourier transform spectrometry [8], but this usually requires significant processing time and also, in order to avoid distortions, a good quality signal, free of polarization fading. It also requires all the gratings to have different wavelengths, limiting the number possible within a given spectral range of the source.

The method of coherence multiplexing [9] has been used to separate out sensors according to their optical path difference (OPD). When illuminated by a broadband source of short coherence length, each interferometric sensor in a chain shows fringe visibility only when interrogated via an optical interferometer having an OPD matching that of the sensor, to within the source coherence length. The method is sometimes termed "white light interferometry", as it is possible, in principle to use white light when path differences are very small.

Principle of Bragg grating multiplexing in the coherence domain

In this paper, we shall report the first work on a coherence multiplexing scheme which allows linear arrays of gratings to be interrogated by a scanned receiving interferometer.

In our new interrogation system (Fig. 1) the gratings in the array are arranged as a number of in-line matched pairs with different spacings

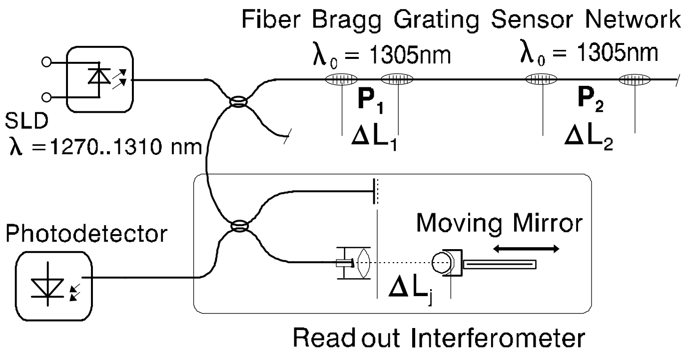

Fig. 1 Evaluation scheme of our new coherence domain multiplexed fiber grating sensor based on pairs of Bragg gratings and scanning readout interferometer.

between each pair. A pathlength-scanned readout interferometer determines, in turn, the centroid wavelengths of each grating pair from the period of each group (burst) of visible interference fringes, formed sequentially as the scanned-interferometer pathlength passes through the path difference of each grating pair.

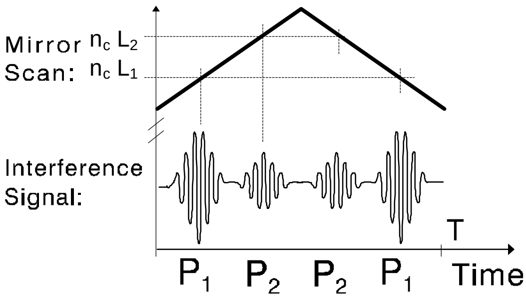

Fig. 2 Schematic view of the interference visibility of two grating pairs P_1 and P_2 during scanning (in each direction) the armlength imbalance in the readout interferometer through their spacings, L_1 and L_2 (n_c - effective refractive index of fiber core).

However, the grating pairs act as a reflective filter, increasing the coherence length of the light-source/grating-pair combination to approximately that of the length of the gratings. In order to avoid undesirable overlap of observed fringes from different pairs of gratings, the spacings of each pair must differ by a "decoherence" length, substantially more than the coherence length represented by the reduced spectral width. Unfortunately, the necessary differences increase if the spectrum of the broadband light source is non-ideal, e.g., with residual narrow mode spectra with high-gain superluminescent diodes (SLDs).

Thus, the readout interferometer selects grating pairs, sequentially, by a process of coherence multiplexing, and simultaneously measures their centroid reflective wavelengths λ_B from the temporal fringe spacing, observed as it scans through. If the readout interferometer varies its pathlength linearly with time, at constant velocity v_M, then the temporal fringe spacing represents an approximately constant frequency f_M of fringes $f_M=2v_M/\lambda_B$.

Experimental results

The multiplexing scheme has been tested experimentally in the arrangement of Fig. 1 with a 1300nm fiber-pigtailed SLD (SLD561) and a 1MΩ transimpedance receiver PRM56/4 (both from Superlum Ltd.). The Bragg grating strain sensor array consisted in the first laboratory test of two fiber grating pairs P_1 and P_2 , formed by UV inscription in standard single mode fiber. The length of each grating was 4mm, the reflectivity R=4..5%, the half-power bandwidth was $\delta\lambda$=0.5nm at a mean wavelength λ_{B0}=1305nm. L_d of the Bragg grating reflections, with bandwidth $\delta\lambda$=0.5nm, was expected to be $L_d=4\cdot\lambda_{B0}^2/\delta\lambda$ =14mm [10]. The spacing between the gratings was L_1=51mm for P_1 and L_2=71mm for P_2. However, in practice, the optical path differences $2n_c\cdot L_1$ (n_c - effective refractive index of fiber core, n_c~1.47) as well as their increments $2n_c\cdot(L_2-L_1)$ were chosen to be much longer than the decoherence length L_d of light reflected from the fiber gratings (for reasons see below).

The fiber section between the grating pairs was set to be greater than 2m, to guarantee that the corresponding reflection signals would no longer contribute to interference.

The Michelson readout interferometer had one fiber endface mirrored by silver coating. The optical path length of the second interferometer arm could be periodically varied: the fiber endface was reflection-free polished under an angle of 8°, the collimated light beam being reflected by a spherical retro-reflector, driven in alternating linear directions with a p-p amplitude L_M=12.5mm by a push-pull solenoid pair.

Separate addressing of the two sensors was performed by adjusting, sequentially, the readout interferometer to a mean retro-reflector position corresponding to an imbalance close to each of the optical pathlengths $n_c\cdot L_1$ and $n_c\cdot L_2$.

The mean velocity of the moving mirror was adjusted to $v_M=L_M/\delta t$=0.55m/s. The resulting mean frequency of interference signal was typically $f_M=2v_M/\lambda_{B0}$ =850kHz. Small deviations $\delta\lambda_B$ from λ_{B0} during mechanically straining (or heating) of a grating pair lead to incremental frequency changes $\delta f_M=-(\delta\lambda_B/\lambda_{B0})\cdot f_M$. For noise reduction, the interference signal at frequency f_M was selectively amplified within a bandwidth of 50kHz. The frequency changes δf_M were determined by counting the interference fringes at maximum interference visibility during the retro-reflector scan. Interval duration of 3ms (pass length of moving retro-reflector 1.7mm) was chosen, where the interference visibility was maximum and the velocity of the retro-reflector was nearly constant in the experiments. We expect later to employ a higher amplitude mirror scanner, to enable all grating pairs to be interrogated in one sweep.

In contrast to the simplified signal shown in Fig. 2, the real system showed full decoherence only at optical path differences >50mm. This was explained by residual ripple (relative height about 10%, period 0.3nm) in the spectrum of the SLD. This caused an undesirable non-monotonous broadening of the coherence, leading in practice to the envelope of the interference signal departing from the ideal Gaussian shape. A long-periodic structure (Fig. 3) appears in the coherence function due to the few (typically 2 or 3) residual SLD Fabry-Perot modes which overlap the 0.5nm halfwidth Bragg grating reflections.

The multiplexing scheme with two Bragg grating pairs was tested as a two-point strain sensor array. Tensile strain was applied immediately to the fiber leads of either grating pairs. At force levels F=0.3N, the fractional strain induced frequency change was $9 \cdot 10^{-4}$/N. From this value, a Bragg wavelength shift coefficient of 1.2nm/N was calculated, in reasonable agreement with that of 1.17nm/N from direct spectral measurement [6].

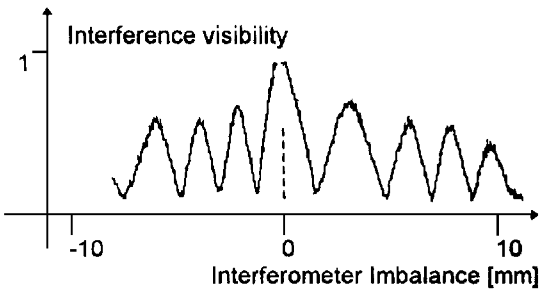

Fig. 3 Interference visibility of a single Bragg grating reflection, as a function of readout interferometer armlength imbalance.
The length scale is nonlinear and is given only approximately. The distance between maxima of coherence is 2.7mm, corresponding to the optical path length of the SLD chip and to the ripple period of 0.3nm in the SLD spectrum.

The absolute frequency shift was $790\text{Hz}\cdot\text{N}^{-1}$ tensile force, or $0.7\text{Hz}\cdot\mu\epsilon^{-1}$. The equivalent temperature sensor would show a frequency shift of $6\text{Hz}\cdot\text{K}^{-1}$.

Conclusion

A new multiplexing scheme of fiber Bragg gratings has been developed and experimentally realized. It uses pairs of gratings with different spacings along a fiber line and with interrogation of their reflections using a scanning Michelson interferometer to separate their returns in the coherence domain. The actual Bragg wavelength of each of the sensor elements can be simultaneously determined during this scanning process by conventional frequency counting of the interference fringes.

Using this technique, a resolution of strain <1µϵ and temperature <0.1K is possible at measuring times ~1s. Similar accuracy of Bragg wavelength determination from the frequency of interference fringes is expected in future by calibrating the measurements using a reference laser wavelength (as, for example, proposed in Ref. 8) and by reducing the polarization and SLD-spectrum-induced errors discussed below.

This new multiplexing scheme of Bragg gratings in the coherence domain needs no optical filters or fast pulsed optoelectronics, but it can be combined with known wavelength and time domain multiplexing methods in order to increase the number of sensors possible in the network.

The spacings of the gratings in each of the individual measuring points had to differ by a much greater amount (about 20mm) than predicted by simple theory. This was caused by the residual Fabry-Perot mode spectrum of the SLD used in the experiment. The use of a broadband light source with a smoother spectral distribution (e.g., fluorescent fiber light source) would allow us to decrease the distance steps to <5mm, as determined from the coherence length corresponding to a 0.5nm wide reflection spectrum of the Bragg gratings, and, therefore, would shorten the overall length of each sensor point.

The undesirable modal structure of the SLD causes also an alternating error of Bragg wavelength determination (observable by Fourier transformation of the SLD spectrum to have a period equal to its mode spacing of 0.3nm).

Calculation, numerical compensation, and experimental verification of this non-linearity, as well as the influence of small Bragg wavelength differences within one grating pair will be reported later, after mechanically improving the sensor interrogation arrangement.

The interference visibility is influenced by drifts of the birefringence in the optical fiber between the fiber coupled Bragg grating pairs, as well as in the fiber optic readout interferometer. Use of polarization scrambling or diversity will increase stability of the interrogation technique.

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