Stabilization in an optical fiber interferometer using semiconductor laser

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ABSTRACT

In this paper we present results of our stabilization scheme for an optical fiber Mach-Zehnder interferometer with a diode laser as light source. It is developed for compensating the drift path difference produced by external parameters as the environmental temperature. The optoelectronic setup in which the interference signal is fed back to the injection current of the laser diode is investigated in order to obtain a stabilized system. Details on parameter characterization, system design and the results observed are given.

Keywords: Semiconductor Laser, Active Homodyne Stabilization, Fiber Optic Interferometer, Composite Materials.

1. INTRODUCTION

Embedding optical fibers into carbon fiber composite material structures allows to use optical interferometric techniques in order to sense material parameters. This is possible since optical fibers present temperature and strain ranges as those within the carbon fiber¹. These two characteristics are of main concern in the principal application of composite materials, that is the aeronautic industry. We can point out that an attractive feature of embedding fibers is that optical interferometric techniques are extremely sensitive.

Nevertheless it is not straightforward to operate interferometric sensors in linear and stable transduction regions avoiding fading of the signal in response to temperature or strain stimuli. This fading is due to variations of the differential drift path as a result of the undesirable fluctuations of environmental temperature and pressure². A good solution to avoid this problem in laboratory experiments is to lock the phase of the interferometer in quadrature with an active homodyne method³.

Piezoelectric actuators are extensively used in order to force changes into the physical path, but many problems arise when optical fiber is embedded in composite materials. Both the size and the isolation from conducting carbon reinforcement fiber introduce difficulties for the integration⁴. Optical fibers can be embedded within composite and should be able to withstand temperature and strain excursions comparable with those under which the material can operate, whereas piezoelectric materials are not recommended in these cases.

An alternative to piezoelectric actuators are semiconductor laser sources. In these devices the emission wavelength can be tuned by changing the magnitude of drive current. By this means, the phase can be modified in an unbalanced interferometer. This technique provides additional advantages as a greater upper frequency, an improved dynamic range and better response when resetting the compensation⁵.

In this paper we investigate the optoelectronic scheme developed at the University Carlos III in collaboration with CASA (An Spanish Aeronautical Company) where a semiconductor laser is used to compensate the optical fluctuations. Characterization of parameters and the feedback loop are studied. We also show results of the optical fiber interferometer stabilization.

This work is presented with the following scheme: First, section II starts with a description of the stabilization concept and the conditions used to develop the optoelectronic setup that is shown in section III. Characterization of the all optoelectronic system parameters is included too. In section IV the results obtained with this system are presented. Finally, in section V, conclusions and some details about future work will be provided.

2. STABILIZATION CONCEPT IN OPTICAL FIBER INTERFEROMETER

Interferometric sensors have a great sensitivity to different physical parameters, and when optical fiber is used as intrinsic transducer, environmental fluctuations of the temperature or strain produce changes in the optical path, causing the path drift. So, to lock the optical phase, some kind of compensation must be provided.

In a Mach-Zehnder optical fiber sensor the optical phase can be expressed by equation (1), where n is the refractive index, L is the physical length and λ is the wavelength of the light. Changes of the refractive index or the length of one arm induce changes in optical phase.

$$\phi = 2\pi n L / \lambda \quad (1)$$

While the compensation schemes using piezoelectric actuators can modify L , when an imbalance (the path difference $L_D \neq 0$) is introduced between the arms of a two beam interferometer, if the wavelength of the light is increased, then differential optical phase between the arms also have a proportional variation as it is expressed in equation (2), where λ and $\Delta\lambda$ are the wavelength and wavelength changes⁶. Thus optical phase changes can be produced by tuning the wavelength of the source in order to compensate those phase displacements due to environmental fluctuations.

$$\Delta\phi_\lambda = 2\pi L_D \cdot \Delta\lambda / \lambda^2 \quad (2)$$

Wavelength optical phase control can be obtained using a semiconductor laser by modifying the injection current of the laser diode. As it is shown in figure 1, when the current increases, both the wavelength and the emission power increase linearly. In the other hand, there is also a relationship between temperature in the diode and the wavelength of the emitting light.

In figure 2 we present the feedback scheme that we have used in our experiment for stabilization. The interferometer is an optical fiber Mach-Zehnder configuration. The recombination of the beams is achieved at the beam-splitter for simplicity. This allows to force different visibility values by fine optical adjustments. As the emission wavelength of the semiconductor laser also changes with source temperature, a temperature stabilization system is necessary⁷. The response of the interferometer in terms of voltage is compared with a reference and the difference is amplified and converted in the error current that is applied into the diode over the bias current.

The error signal can be alternatively extracted from the difference between the signals in two photodetectors where the two outputs of the interferometer were taken. Since these signals are displaced in π radians of phase path difference, the effect of changes in the power emission of the source and other common fluctuations can be avoided. But, as both outputs have not the same DC level, it is necessary to compare each one with a reference before subtraction be done. Then, we have chosen the simplified scheme mentioned above. In this case, reference could be adjusted to lock the response at different levels, where more sensibility region (in quadrature) is reference equal to output DC.

There could be used an integrator for loop bandwidth electronic selectivity. By these means, the stabilization is limited to a bandwidth higher than the frequently low frequencies associated to environmental changes. Other loops in different bandwidth and gain can be aided for feedback, each one selective in the response frequency of the system.

3. EXPERIMENTAL OPTOELECTRONIC SETUP

The semiconductor laser that has been used in the experiment (CQL801D Phillips) has a wavelength dependence with current of about 0.0045 nm/mA⁸. This data have been experimentally characterized in a free space unbalanced Michelson interferometer by modulating the current injected, and compared satisfactory with the results observed with a monochromator.

In figure 3 we present the differential optical phase versus current for this characterization system. The physical imbalance between two arms in the Michelson interferometer is 2,5 cm (5 cm path difference). The method used was to count periods of the intensity function (2π phase displacement) forced by modulation of laser current with different values of amplitude. Several initial DC and AC signal shapes have been used. We had observed changes about 10π radians in optic phase when semiconductor laser is modulated with ramp signal of 10 mA and 5 cm interferometer path difference. So the linear response is about π rad/mA that agrees with which we have presented before ($\approx 0,00449$ nm/mA).

Figure 4 shows the interferometric signal when the current injected into the laser diode is linearly varied. Two cases with different amplitude levels are presented (4 mA_{pp} and 10 mA_{pp}) as an example with an all fiber system whose path difference is about 4,5 cm. We can see the interferometric signal following the cosine function over the modulation signal. Each period of the intensity response is 2π rad optical phase.

In the case of small amplitude changes of current, the contribution of the power modulation of the source is much lower than those produced by phase modulation of the interferometric intensity (see figure 4a). The greater are the visibility and sensibility phase to current ($\Delta\phi/\Delta i$) the lower is the contribution of the power changes.

The compensation range (the greatest phase change that is possible to correct with the current injected to the laser) may be increased through L_D . We have observed that the laser that we have used in our stabilization experiment provides a good performance when L_D is set to 25 cm, so $\Delta\phi/\Delta i$ can be $2,5 \pi \text{ rad/mA}$.

Besides the Michelson interferometer for characterization of wavelength versus injection current, three Mach-Zehnder optical fiber schemes have been tested: 1) fiber arms and beam-splitters in division and recombination, 2) all fiber interferometer and 3) coupler in division and beam-splitter in recombination.

Afterwards we have used a coupler for division in order to make easy the comparison between different semiconductor lasers and a beam-splitter in recombination for adjustment of the visibility. Although the coupler specification for splitting is 50%, we have observed 60%-40% in practice.

We have compared two semiconductor lasers: Philips CQL801D series whose wavelength is 670 nm., maximum power 15 mW and current changes range of 30 mA; and Mitsubishi ML1412R multiple quantum well with wavelength of 690 nm, power up to 35 mW and current range of 40 mA. By comparing the visibility with those obtained with a large coherence length laser (He-Ne) we have chosen CQL801D laser, because ML1412R shows appreciable visibility changes.

A path difference L_D of 20 cm between the two arms of the interferometer has been used in order to work in the linear region sinusoidal signal output between $\pi/2$ and $3\pi/2$, for creating an error signal up to 0,25 mA. The dynamic range of the diode is 30 mA_{pp} , so the maximum range of phase compensation with this scheme is 60π radians.

Finally, a wide area photodiode BPW34 focused in the main disk of the fringe pattern has been used. We have inserted spatial filter in order to reduce the beam integration area.

The detector electronics is mainly composed by a current to voltage (I-V) amplifier with offset compensation. The feedback signal that is used results from the addition of the reference voltage level and the signal from the detector. The reference voltage level is calibrated in quadrature. Any deviation from this reference produces a feedback signal with the same sign.

The current driver for the laser adds the voltage to biasing the current source for the diode and the feedback voltage after frequency filtering and amplification ($4 \text{ volts}/\pi \text{ rad}$). A voltage to current (V-I) amplifier with a bipolar transistor supply the injection current up to 60 mA. The sensibility of the driver is 2 mA/V for the feedback voltage.

4. RESULTS

In figure 6 we show the response of our system in two free running intervals among three of closed loop. As we can see the response of the interferometer is stopped around zero intensity level of output signal corresponding to phase lock to $\pi/4$ relative phase shift.

Other levels have been forced successfully by fixing different references. The system withstand changes in visibility and emission power of the source. In these cases adjustment with the reference are proved.

In figure number 7 we show a detail of the response of the system in terms of intensity in the output of the interferometer that is the feedback signal (channel 3), power of the laser in the monitor photodetector (channel 1) and current injected in the diode (channel 4).

As we can appreciate in the figure 7 the output of the interferometer varies when no stabilization is applied whereas the semiconductor laser current and the output of monitor photodiode are constant.

However, when the interferometer is under locking conditions, the intensity of the interferometer is constant, which means the phase is tracked by current injection of the semiconductor laser, while the current injection and the output of photodiode monitor fluctuates in order to compensate the phase drift.

These results of the stabilization interferometer show that the free running fluctuations of phase are compensated about few 10^{-2} parts over 2π phase drift. It can be seen in figure 7 that this phase compensation is accompanied with a much more level of intensity light fluctuations than the current injection of the semiconductor laser. We can appreciate in this figure that the intensity current fluctuates 50% less than the intensity light of the semiconductor laser. Then, this means that a phase noise contribution from semiconductor laser source is present⁹. In order to improve the phase compensation of the interferometer the semiconductor laser source should be single frequency (better than 20 dB mode suppression ratio) and less phase noisy.

5. CONCLUSIONS AND FUTURE WORK

In this work we presents results of our stabilization scheme in order to compensate different external parameters as the environmental temperature. This scheme is working now as a prototype developed by our Research group in collaboration with the Spanish Aeronautic Company (CASA) for stabilization of a temperature gradient sensor using interferometer of optical fiber embedded in composite materials.

Once the loop has been studied and working we will characterize the response of a carbon sample to temperature steps and differential temperature (0 - 100°C). In figure 8 carbon fiber sample and instrumentation for temperature measurement are shown. Those temperature measurements are now undertaken.

This work is in the context of characterization by optoelectronic means of composite material panels used in aerospace vehicles, avionics and satellites, through the response to different physical magnitudes like temperature and strain.

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Figure 1. Emission light intensity (a) and wavelength (b) versus injection current in the semiconductor lasers.

Figure 2. Optoelectronic Scheme for stabilisation.

Figure 3. Optical differential phase versus laser diode current in a Michelson interferometer with imbalance of 5 cm.

Figure 4. Interference response to a modulation of the semiconductor laser with different amplitudes of the input signal in an all fiber Mach-Zehnder configuration.

Figure 5: Output intensity of Mach-Zehnder interferometer in free running.

Figure 8. Carbon fibre plate detail with electronic heaters instrumentation in order to make temperature gradients of 100°C.