Optical Fiber Technology 53 (2019) 102009

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Self-referencing optical intensity sensor based on radio-frequency spectrum interrogation

M. Roslina[a], M.R. Mokhtar[b,*]

[a] College of Engineering, Universiti Tenaga Nasional, 43000 Kajang, Selangor, Malaysia
[b] Research Institute for Digital Connectivity, Multimedia University, 63100 Cyberjaya, Selangor, Malaysia

A R T I C L E I N F O

Keywords:
Fiber optic sensor
Optical sensor network
Optical multiplexing
Self-referencing

A B S T R A C T

This paper proposes an optical sensor system that is based on non-interfering optical power superposition in Mach-Zehnder configuration. The sensor generates radio-frequency (RF) spectrum that responds to the imbalance of optical power between the branches of the Mach-Zehnder structure induced by the sensing measurand. The sensing signal provides self-referencing intensity-based interrogation without requiring typical expensive optical frequency apparatus and complicated signal processing technique. Its reliability is demonstrated in a load sensing application.

1. Introduction

Fiber optic sensors are known to have desirable properties such as multiplexable, non-electrical, remote capability and high sensitivity [1]. Due to these advantages, they have been successfully deployed in many applications, wherein the reactions of wavelength, phase or amplitude of the lightwave have been demonstrated as the sensing mechanisms for interaction between sensing element and the measurands [2]. The interrogation of signals for extraction of measurement values may involve interferometric spectral pattern, wavelength shift, or intensity change.

Typically, retrieval of the wide optical spectrum of the sensors output is required in order to be able to analyze and interpret the measurement values, in particular when it involves interferometric spectral pattern or wavelength shift [3]. Obviously, expensive apparatus operating at optical frequencies need to be utilized. Furthermore, processing and analysis of the data are usually calculation-intensive and time-consuming.

Alternatively, interrogation based on intensity change offers a more straightforward process, which translates into cheaper system cost and simpler system construction [4]. This approach exploits waveguide loss or phase-to-intensity conversion by the sensing element when exposed to the measurand. Among the techniques adopted to realize waveguide loss are macro-bending, mode-radiation and dynamic filtering. On the other hand, the conversion from the phase change to the intensity change is achieved by exploiting interference principle, built upon the typical Mach-Zehnder, Michelson or Sagnac interferometer configurations [5].

However, variation of the optical power of input to the sensing element raises uncertainty on the absolute values obtained from the measurement [6]. Various unavoidable factors may contribute to this power variation, such as the intensity of the light source, the system component loss, the frequency response of the source and detector and the coupling efficiency of optical apparatus. The presence of the power variation that also leads to inaccurate measurements and limited resolution has lately attracted research interests in finding the solutions, where some of the demonstrated techniques are spatial referencing [7], spectral splitting [8], and amplitude-phase conversion [9]. These techniques, however, have complex setups and interrogation processes.

In addition to the power variation issue, these intensity-based sensors typically have broadband spectral responses, which renders them unsuitable for large scale sensing applications. The common wavelength-division multiplexing (WDM) scheme does not allow overlapping of spectra, while the optical time-division multiplexing (OTDM) scheme makes the system complex due to temporal synchronization requirement [10].

This paper presents an intensity-based optical sensor system with self-referenced capability through straightforward interrogation in RF domain. Its reliability is validated in a load sensing application, which incorporates characterization on linearity of response and immunity to power variation. The proposed sensor system involves translation from optical signal into RF signal, which promises a cost-efficient system and implies multiplexing potential.

* Corresponding author.
E-mail address: ridz@mmu.edu.my (M.R. Mokhtar).

https://doi.org/10.1016/j.yofte.2019.102009
Received 10 May 2019; Received in revised form 26 July 2019; Accepted 29 August 2019
Available online 16 September 2019
1068-5200/

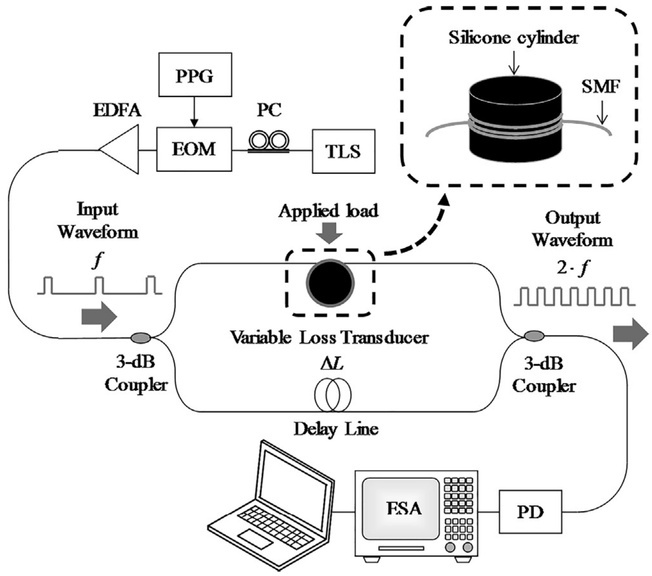

Fig. 1. Schematic diagrams of the optical fiber sensor system.

2. Device principle and description

The optical fiber sensor is formed by adopting the Mach-Zehnder configuration, which is constructed by cascading two 3-dB couplers, as shown in Fig. 1. However, instead of realizing an interferometer, the Mach-Zehnder configuration is actually intended to cause the modulation frequency of the input pulse train to be doubled upon emerging from the structure output. For this reason, the branches are designed with different lengths with the amount dictated by,

$$\Delta L = \frac{c}{2nf} \tag{1}$$

where ΔL is the length difference between branches, c is the speed of light travel in vacuum, n is the effective refractive index of the optical fiber, and f is the modulation frequency of the light source for the sensor input in the form of a pulse stream. This length difference between the branches causes the pulse trains from the two branches to interweave at the output coupler, thus doubles the pulse rate. It is noted that the proposed sensor can be configured to various modulation frequencies, thus it obviously has multiplexing capability in the electrical frequency domain. This is advantageous in the sense that multiple sensors can share the same optical wavelength and the sensing network will not require complicated temporal synchronization between the transmitting and receiving terminals.

In order to produce a pure (i.e. well-defined) output RF spectrum at doubled of the input frequency, the interweaving process requires high precision positioning of the pulse train from one branch onto exactly the middle span between the pulses from the other branch. In this configuration, the delay caused by the length difference may also be affected by temperature and strain of the surrounding environment. Additionally, the pulses need to be sufficiently isolated from each other to prevent overlapping and interference in the interweaving process. Consequently, it is desirable to set a low duty cycle in the waveform generator.

A variable loss transducer is placed in one of the arms for the purpose of inducing optical power imbalance in response to the change of measurand values. In this demonstration, the variable loss transducer exploits macro-bending loss, which is achieved by winding a length of single-mode optical fiber with a numerical aperture (NA) of ~0.13 and an effective refractive index, n of ~1.46 around a silicone cylinder with a diameter of 30 mm, as shown in the inset of Fig. 1. Three sets of the variable loss transducers are prepared, which have the number of turns of 1, 5 and 10 turns for the purpose of analyzing the sensor sensitivity. The silicone is chosen because of its flexibility, low cost and resistance to chemicals and decomposition. The silicone cylinder will deform into oval shape when a load is applied, wherein the change in shape subsequently causes the bending radius of the wrapped fiber to be reduced and thus increases the bending loss. Each time after the load is applied and later lifted, the silicone cylinder will always return to their initial shape.

The proposed sensor system is totally different from the typical interferometric sensor setups that utilize the similar Mach-Zehnder structure, such as in [5], whereby the interferometric sensors strictly rely on the principle of interference, whereas the proposed sensor is astutely based on the non-interfering superposition principle. Furthermore, in the former sensor setup, in order to achieve self-referencing, it requires conversion from amplitude to phase [9], which is definitely not required in the proposed sensor system. Therefore, it is obvious that the proposed sensor system has simpler and straightforward operation and post-detection processing.

3. Sensing experiment and result

The characterization setup is composed of an optical pulse transmitter and an electrical receiver, as illustrated in Fig. 1. For the transmitter, a tunable laser source (TLS) set at a wavelength of 1553 nm, is used as the light source, and the pulse stream is generated by externally modulating the TLS output with an electro-optic modulator (EOM). The EOM is driven by a 20 MHz electrical pulse signal with a duty cycle of 2% from a digital pulse pattern generator (PPG), thus producing pulses with a pulse width of approximately 1 ns. Obviously, a directly-modulated single-wavelength diode laser can be utilized to construct a much simpler and lower cost optical pulse transmitter. For the other approaches that are based on interferometric spectral pattern or wavelength shift, it is inevitable for them to use a costly light source with a broad range of wavelengths. A polarization controller (PC) is used to adjust the polarization state for optimum operation of EOM. In order to compensate for the insertion loss by the EOM and the splitting losses later, the optical pulse train is amplified by an erbium-doped fiber amplifier (EDFA) before being split equally by a 3-dB coupler into the two arms of the Mach-Zehnder structure. The replica of the pulse train is delayed in one of the arms by an optical fiber delay line, and is later recombined with the pulse train replica from the other arm at the second 3-dB coupler. After the recombination, the optical sensing signal with doubled modulation frequency is captured by the receiver, composed of a photo-detector (PD) that converts the optical signal into electrical signal and an electrical spectrum analyzer (ESA) that displays the RF spectrum. Here lies a substantial cost saving in comparison to the approaches that require the use of optical spectrum analyzer (OSA) that is typically priced at several folds higher.

The signal data is processed to extract the generated RF spectrum peaks, wherein the visibility, v value is then calculated by following the formula below,

$$v = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}} \tag{2}$$

where P_{max} is the maximum spectrum peak value and P_{min} is the minimum spectrum peak value in units of decibels. This measurement process is performed for the sensors with different number of turns, as well as for varying input optical power values. The sensor is subjected to load with mass of up to 11 kg.

It is observed that when the optical power between the two branches of the Mach-Zehnder structure is perfectly balanced, the ESA shows a pure frequency component at double of the input modulation frequency, which is 40 MHz, as shown in Fig. 2(a). As the sensor is perturbed due to the applied load, which consequently results in power imbalance, the original input modulation frequency component at 20 MHz begins to reappear. However, due to equipment limitation, wherein its considerable background low frequency noise of the

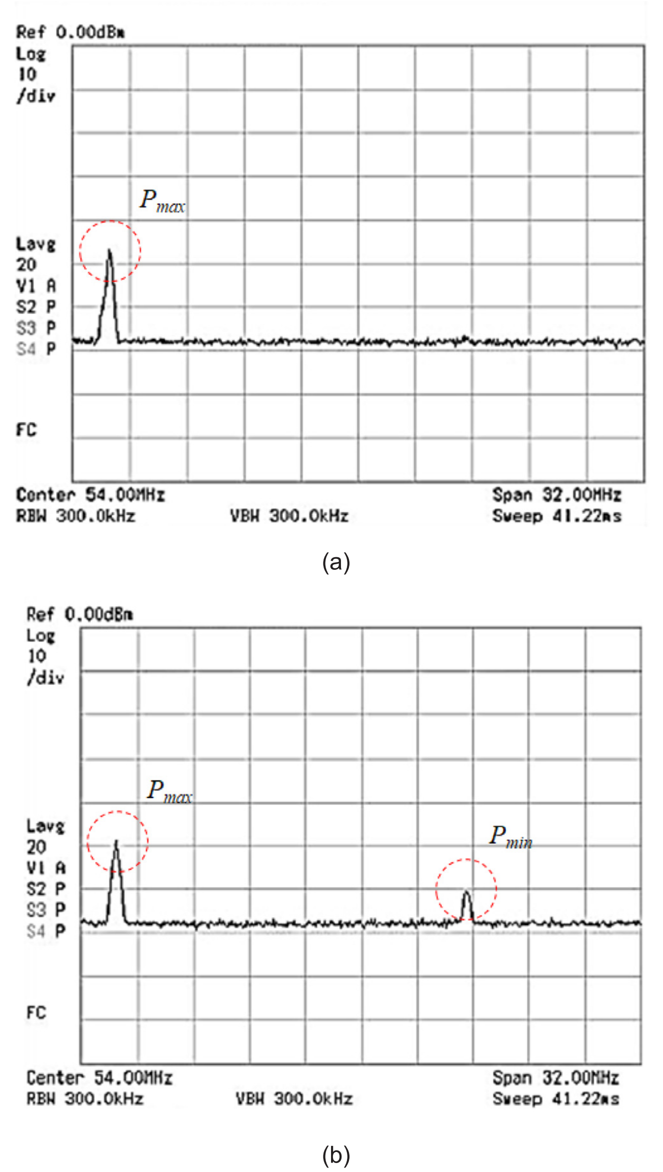

Fig. 2. ESA spectrum with (a) no load, (b) applied load.

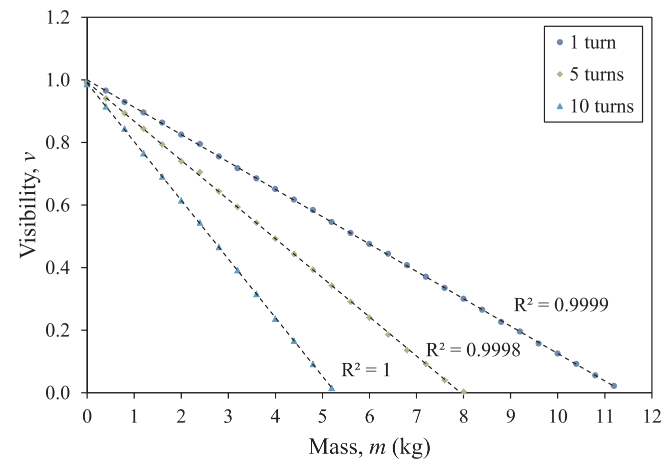

Fig. 3. Relationship between visibility and load mass for various number of wrapping turns.

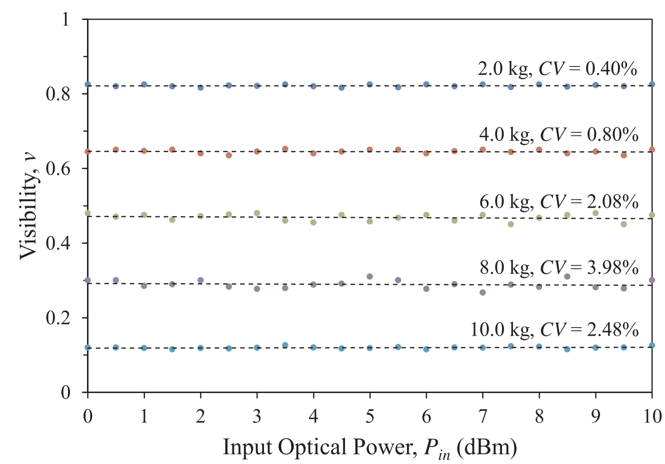

Fig. 4. Calculated visibility against input optical power for various load mass values.

equipment extends up to around 30 MHz, its harmonic component at 60 MHz on ESA is instead referred to for the measurement, as shown in Fig. 2(b).

The values of visibility, v is plotted against the load mass for the sensors with the number of turns of 1, 5 and 10, as shown in Fig. 3. It shows a desirable linear relationship with the coefficient of determination, R^2 of at least 99.98%. The gradients of the lines also represent the sensor sensitivity, which is observed to increase with the number of turns. The sensitivities for the sensors with the number of turns of 1, 5 and 10, are calculated to be $-0.0874\,\text{kg}^{-1}$, $-0.1251\,\text{kg}^{-1}$ and $-0.1874\,\text{kg}^{-1}$, respectively. This is expected as the region of bending is proportionately extended as the number of turns increases. As a given load mass compresses the flexible silicon cylinder from the top direction, the silicon will deform into a specific oval shape with a reduced curvature radius at both right and left sides of the cylinder that induces higher bending loss. As the propagating light repeatedly encounters more of these smaller bending regions when the cycle of turns is increased, the light signal will accumulate higher transmission loss as it exits the fiber winding.

The effect of input power variation is also experimented by increasing its values from 0 up to 10 dBm with a step of 0.5 dBm. The results for several load masses on the sensor with 1 wrapping turn are shown in Fig. 4, which indicates that variation in the input optical power hardly affects the visibility, wherein the worst calculated *coefficient of variation (CV)* is only 3.98%. This undoubtedly proves the ability of the sensor for self-referencing.

4. Conclusions

A new approach to achieve self-referenced optical sensing by RF spectrum interrogation has been discussed and demonstrated in this paper. This approach simply exploits the optical power imbalance between the branches of a Mach-Zehnder structure induced by the sensing measurand to vary the response of the generated RF spectrum. Its application is demonstrated in a load sensing experiment wherein the sensor exhibits a linear response with the applied load, and is immune to any variation in the input optical power, with the coefficient of variation of not more than 4%. Moreover, the sensor system uses uncomplicated data processing and has capability of multiplexing. This approach can be adopted for myriad applications by simply replacing the power loss transducer that is receptive to the desired measurand. Examples of applications are pressure and temperature sensors, with macro-bending mechanism, and long-period grating as the power loss transducer, respectively.

Acknowledgments

This work was supported by the Ministry of Higher Education Malaysia under the Exploratory Research Grant Scheme (EP20120612002). The authors wish to thank Z. Yusoff and H. A. Abdul Rashid for their valuable help.

References

[1] K.T.V. Grattan, T. Sun, Fiber optic sensor technology: an overview, Sens. Actuators, A Phys. 82 (1) (2000) 40–61.
[2] B. Culshaw, Optical fiber sensor technologies: opportunities and perhaps pitfalls, J. Lightwave Technol. 22 (1) (2004) 39–50.
[3] F. Zou, Y. Liu, C. Deng, Y. Dong, S. Zhu, T. Wang, Refractive index sensitivity of nano-film coated long-period fiber gratings, Opt. Exp. 23 (2) (2015) 1114–1124.
[4] H.-X. Zhang, Y.-L. Hou, L.-S. Feng, S. Su, J.-W. Zhang, J. Liu, W.-Y. Liu, J. Liu, J.-J. Xiong, Polymer optical fiber continuous liquid level sensor for dynamic measurement, IEEE Sens. J. 15 (9) (2015) 5238–5242.
[5] S. Wang, P. Lu, L. Mao, D. Liu, S. Jiang, Cascaded interferometers structure based on dual-pass Mach-Zehnder interferometer and Sagnac interferometer for dual-parameter sensing, Opt. Exp. 23 (2) (2015) 674–680.
[6] Carmen V'azquez, Julio Montalvo, David S. Montero, Pedro C. Lallana, Self-referencing technique in photonics sensors and multiplexing, in: Proc. SPIE Photon. Mat. Dev. and App. II 6593 (2007) 1X-1-11.
[7] G. Murtaza, J.M. Senior, Referenced intensity-based optical fiber sensors, Int. J. Optoelectron. 9 (4) (1994) 339–348.
[8] Anbo Wang, Hai Xiao, J. Wang, Zhiyong Wang, W. Zhao, R.G. May, Self-calibrated interferometric-intensity-based optical fiber sensors, J. Lightwave Technol. 19 (10) (2001) 1495–1501.
[9] Jose Manuel Baptista, Jose Luis Santos, Armindo L.V.S. Lage, Mach-Zehnder and Michelson topologies for self-referencing fiber optic intensity sensors, Opt. Eng. 39 (6) (2000) 1636–1644.
[10] J.D.C. Jones, R. McBride, Multiplexing optical fiber sensors, in: K.T.V. Grattan, B.T. Meggitt (Eds.), Chap. 4: Optical Fiber Sensor Technology - Devices and Technology II, Chapman and Hall, London, 1998, pp. 117–166.