Paper ID #49619

Modeling of Optical Sensors Incorporating Optical Amplifiers

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Abstract

The objective of this study is to investigate the sensitivity of recirculating delay line (RDL) and Mach-Zender (M-Z) interferometers when an optical amplifier is introduced in the fiber feedback loop. Although this study is only a simulation, we will explore the practical application of introducing optical amplifier in integrated optical circuits as we expand the sensor lab. The RDL and M-Z interferometers have a maximum sensitivity to the measurand as well as to any noise variable. However, the M-Z interferometer with a feedback path, the sensitivity to other variables such as the temperature and the wavelength changes, can be eliminated by the common mode compensation. In the study new optical fiber interferometers are analyzed and simulated. The purpose of the optical amplifier is to compensate for the strength and phase losses through the couplers and optical fibers. The new optical circuits consist of a RDL and a M-Z interferometer with feedback path, where an optical amplifier is introduced in the feedback loop to compensate for the losses due to the couplers and the splices as well as for the attenuation in the fiber itself. The transmittance of the circuit, which is the ratio of the output intensity to the input intensity, is calculated and plotted for different gain factors of the amplifier. Both weak and strong coupling are considered for the coupler.

Keywords: Recirculating Delay Line (RDL), Mac-Zender (M-Z) interferometer, Fabry Perrot structures, Optical Amplifier.

I. Introduction

In sensing scheme Interferometric sensor is used, where a measurand modulates the phase of a propagating optical field, and the phase change is converted to an intensity signal by the optical interference. Mach-Zehnder interferometer is one scheme of interferometers, which consists of two waveguides sandwiched between two directional couplers. A modified form of conventional Mach-Zehnder interferometer (MZI) with a provision of a feedback path was studied by Buckman who showed how the slope sensitivity can be greatly enhanced using the RF-MZI interferometer geometry[1]. While Ping et al. had Presented a temperature stable fiber optic MZI[2]

In a sensing scheme, an interferometric sensor is employed, where the measurand modulates the phase of a propagating optical field. This phase modulation is then converted into an intensity signal through optical interference. One widely used type of interferometer is the Mach-Zehnder Interferometer (MZI), which comprises two waveguides positioned between two directional couplers. A modified version of the conventional MZI, incorporating a feedback path, has been explored to demonstrate significant enhancements in slope sensitivity. This innovative design, referred to as the RF-MZI interferometer, showcases improved performance and precision. Additionally, a temperature-stable fiber optic version of the MZI has been developed and thoroughly documented, emphasizing its potential for robust and reliable sensing applications in varying environmental conditions.

The effect of the amplifiers in the feedback loop is the addition of new parameters that enable the controlling of the frequency response. Depending on the amplifier's gain and saturation output power, the resulting circuit may exhibit certain advantages in comparison with the classical passive-delay loops. The performance of single and double all-fiber recirculating delay lines is discussed by Vizoso at al[3].

Because of its high bandwidth and high-speed transmission, the optic fiber technology is expanding in the sensors and filter design areas[4]. However, all the connection in fiber optic are generated either by couplers or splices. Splices, which usually are more expensive than couplers, may introduce different attenuations. Couplers, in the other hand, introduce power division which is lost unless used otherwise. In the past, electronic repeaters have been used to compensate for the power division and for the different attenuations. Electronic repeaters generally introduce a bandwidth limitation and an electronic noise that limits the minimum measurand detectable[5]. Semiconductor laser amplifiers have been the object of intense study in order to determine their utility as optical preamplifiers and linear repeaters in fiber optic communication systems. An optical amplifier, having sufficient gain to compensate for attenuations suffered as the signal propagates through the fiber and splices, has been considered for optical local networks systems[6]. Since the amplification process is entirely optical, the time delay introduced by the optical amplifier is minimum. The incorporation of an optical amplifier in an optical sensor is investigated from different point of view. Our aim by such a configuration is to enhance the capabilities of the optical sensor by overcoming some of its present problems.

And on other hand B. Moslehi and J.W stated that analytical results are presented for both amplified and un-amplified fiber-optic recirculating delay lines (AFORDL and UFORDL)[7]. In the AFORDL an OA is inserted in the fiber loop. The active AFORDL structure is capable of realizing all-fiber filters not possible with the passive UFORDL. Again, the design of an optical filter of wide adjustable finesse is possible by changing only the coupling coefficient of the electro-optical directional couplers, leaving the gain of the fiber amplifier unchanged[8]. The intricacies of Nonrecirculating and Recirculating Delay Line Loop (NDLL and RDLL) topologies have been thoroughly examined and analyzed by K. Goel, offering a comprehensive understanding of their design principles and operational dynamics[9]. A similar outcome has been achieved in our study using fewer couplers, as noted by Chao and Guo. While NDLL is proposed for frequency selectivity and RDLL for notch applications, our findings reveal that both functionalities can be realized within the same configuration by varying the gain under conditions of weak coupling[10].

II. Optical Amplifier

Semiconductor optical amplifiers have been investigated for use in fiber optic communication systems, and local area network systems. Traveling-wave (TW) and Fabry-Perrot (FP) were the focus of many researchers. Optical amplifiers magnify the light trough stimulated emission. However, stimulation emission is usually accompanied by a spontaneous emission per mode that constitutes the internal noise of the amplifier. Traveling wave amplifier has perfect antireflection facet coatings, the light beam travels once through the junction. Since always there are reflections, the real TW amplifies are actually resonant cavities. They are considered as Fabry Perrot structures. The peak gain of the central longitudinal mode is:

$$G = \frac{G_0(1-R_1)(1-R_2)}{(1-G_0\sqrt{R_1R_2})^2} \tag{1}$$

For simplicity, we shall assume a TW amplifier with perfect facet coatings, and fundamental mode propagation:

$$G_0 = e^{(g_0-\alpha_0)L} \tag{2}$$

Unfortunately, the physical properties of the optical amplifier limit its application in the sensing area for many reasons. For instance, the amplifier adds its own quantum noise to the signal (intensity and phase noise). Furthermore, the gain of the optical amplifier is limited by gain saturation phenomena, as the input power is raised beyond a certain saturation level, the maximum achievable gain drops with further increase in input power.

III. Optical Circuit

Passive components used in many optical systems include directional couplers, power dividers star coupler, wavelength multiplexers, splices and optical switches. In this study only directional couplers and splices are considered. Directional couplers are used to allow a fraction of the light propagating through an optical fiber to be removed or to be added at an intermediate point along the fiber circuit. A directional coupler has two input ports and two output ports. Using the network circuit theory approach, the coupler can be modeled by the following matrix equation:

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} A & B \\ B & A \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} \tag{3}$$

Where E1, E2, E3, E4 are the optical field amplitudes, and:

$$A = \mathrm{a}e^{jg}\cos(\beta) \tag{4a}$$
$$B = \mathrm{a}e^{jh}\sin(\beta) \tag{4b}$$

For realistic couplers, a and b will be slightly less than unity, and h, g <<1 rad. When many couplers are connected in cascade fashion, their characteristic matrices will be simply multiplied as in classical circuit theory. Expressing the final matrix as follows:

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} \tag{5}$$

So, when a feedback path is introduced between output E3 and input E2, the transmittance of the circuit (the ratio of the output intensity to the input intensity) can be evaluated as follows:

$$T = \left(\frac{E_4}{E_1}\right)^2 = \left(\frac{C_{21} + (C_{11}C_{22} - C_{12}C_{21})t_f e^{jp}}{1 - C_{12}t_f e^{jp}}\right)^2 \tag{6}$$

Where tf is the field transmittance coefficient in the feedback fiber, and p is the phase delay introduced by the length of the fiber. The considered optical circuit consists of a RDL with an optical amplifier connected in series with the optrode in the feedback loop path. Exchanging t_f by $G_0 t_f$ in equation (1), the transmittance of the circuit can be written as:

$$T = \left(\frac{j\sin(\beta) + G_0 t_f e^{jp}}{1 - j\sin(\beta) G_0 t_f e^{jp}}\right)^2 \tag{7}$$

IV. Results and Discussion

To simplify the simulation, all the losses and phase shifts generated by either the splices or the fiber itself are lumped in t_f and phase p. The transmittance of the RDL with optical amplifier shows that the gain of the optical amplifier is directly multiplied by the attenuation coefficient. The sensitivity of the sensor can be controlled by simply changing the gain of the amplifier (Figure 1). The depth of the transmittance can go to zero for a proper choice of the gain. For small gain the transmittance of the circuit is kept between 0 and 1. As the gain increases the transmittance becomes greater than unity. The output intensity is then amplified. Even for a strong coupling in the coupler, the sensitivity of the circuit is enhanced by increasing the gain of the optical amplifier (Figure 2). The gain is generally higher than that required for the weak coupling. Such increase in the sensitivity was not possible without the optical amplifier.

V. Conclusion

In this study we simulated the introduction of optical amplifiers in optical fiber sensors. We demonstrated that the optical amplifier could compensate for the losses generated by the RDL, however, it does not compensate for other environmental variables. The common mode compensation is not possible for the RDL circuit. However, the use of the MZ line with feedback can eliminate such problems. The above simulation shows that the use of an optical amplifier can completely compensate for the different losses generated in the optical circuit. Such design is appropriate for integrated optics. However, if the optical amplifier is not stable enough it can generate intensity and phase noises that may not compensated by an optical circuit that allows the common mode compensation. Furthermore, the incorporation of an optical amplifier can increase the cost of the sensor. In future work, we will investigate the practical application of the concept of optical amplifiers in optical fiber sensors as we build experimental expertise in the sensor lab. Ultimately, we would hope to integrate optical amplifier in integrated optical circuits.

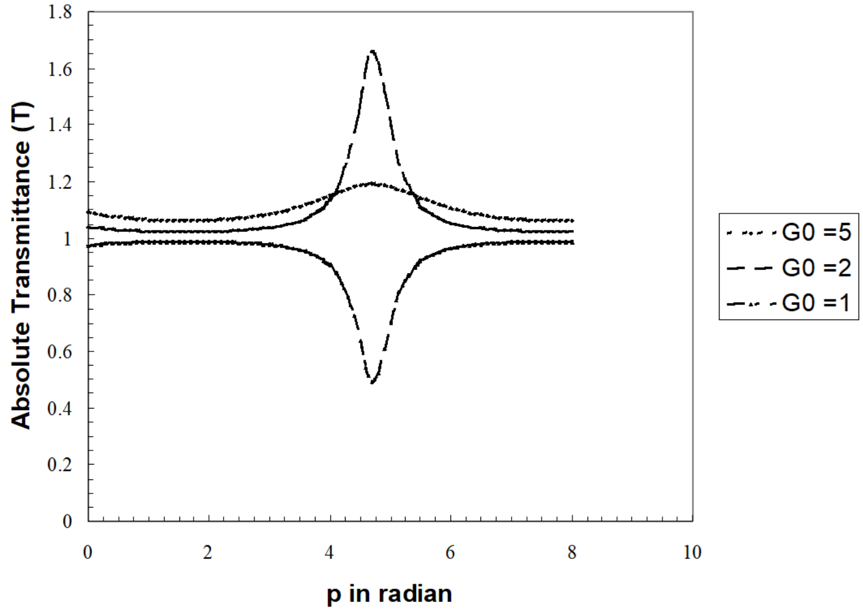

Figure 1: Illustration of the Absolute Transmittance sensitivity of the RDL with optical amplifier with small gains

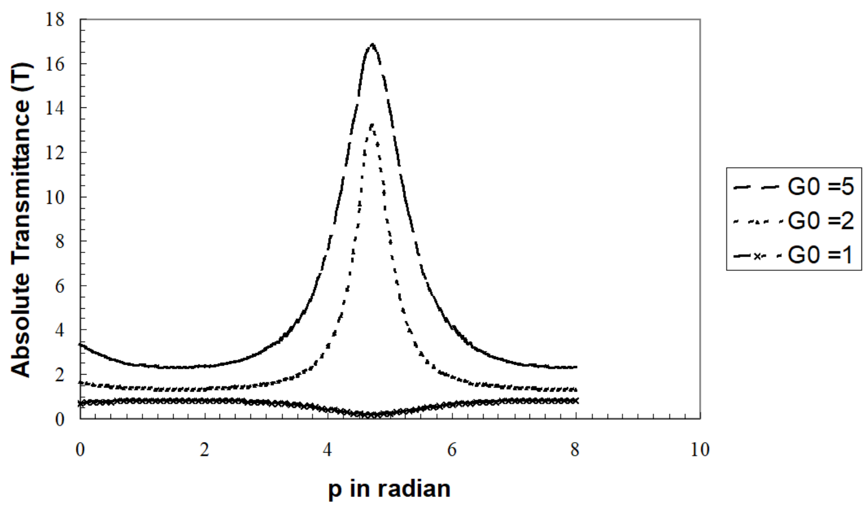

Figure 2: Illustration of the Absolute Transmittance sensitivity of the RDL with optical amplifier with large gains

References

1. A. B. Buckman, "Analysis on a novel optical fiber interferometer with common-mode compensation," *IEEE J. Lightwave Tech*. 7,151-157 (1989).
2. Lu Ping et. El, "Study of Temperature Stability for Fiber-Optic Mach-Zehnder Interferometer Filter", *3rd International Conference on Microwave and Millimeter Wave Technology Proceedings*, 0-7803-7486-/X/02, pp. 1087-1089, 2002.
3. Vizoso Beatriz, Vazquez Carmen and Civera Rafael, "Amplified Fiber-Optic Recirculating Delay Lines" *IEEE Journal of Lightwave Technology*, Volume 12, No. 2, pp 294-304, February 1994.
4. M. Ferdjallah and H. Bouchareb, "A New Synthesis Procedure for Designing Digital Filters Based on Optical Fiber Structures", *ASEE North Central Section Conference*, Morgantown WV, 2023, March 24-25, 2023.
5. D. Fye, " Practical limitations on optical amplifier performance," *IEEE J. Lightwave Tech*. 2,403-406 (1984).
6. S. S. Wagner, "Optical amplifier applications in fiber optic local networks," *IEEE Transactions on Communications* 35,419-426, 1987.
7. B. Moslehi and J. W. Goodman, "Novel Amplified Fiber-Optic Recirculating Dealy Line Processor" *IEEE Journal of Lightwave Technology*, Volume 10, No. 8, pp1142-1147, August 1992.
8. Y. H. Chew, T. T. Tjhung and F. V. C Mendis, "An Optical Filter of Adjustable Finesse Using an Amplified Fiber Ring Resonator", *IEEE Journal of Lightwave Technology*, pp.364-370, Vol. 15, No. 2, February 1997.
9. K. K. Goel, "New Topologies of Fiber-optic Delay Line Filters", *IEEE Photonics Technology Letters*, Vol. 5, No. 9, pp. 1086-1088, September 1993.
10. C. Y. Chao and L.J Guo, "A New Interferometric Sensor with Ring-Feedback MZI**",** *IEEE***,** 0-7803-81 33-5/03, pp.569-572.