SIMULATION AND MEASUREMENT OF MACH-ZEHNDER INTERFEROMETER

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Abstract: The paper focuses on simulation and measurement of Mach-Zehnder interferometer. This type of sensor is used as a distributed fiber optic sensor for sensing vibration, mechanical tension and temperature. Fiber optic sensors based on optical interferometry are now widely used, e.g. Sagnac interferometer in optic gyroscopes. Mach-Zehnder interferometer is used for measurement of transformers temperature. The article includes a simulation of interferometric systems in VPIphotonics simulation software and it also includes scientific notation of a signal and a short description of the used simulation systems.

Keywords: Fiber optic sensors, Mach–Zehnder interferometer, Simulations, VPIphotonics, Measurement.

1 INTRODUCTION

Nowadays, optic sensors are widely used for temperature sensing, mechanical sensing, pressure sensing or vibration sensing due to their physical properties. Optical sensors are resistant to high temperature, and also accuracy of the sensing vibrations and pressure is very good. These dynamic processes involve time–varying signals such as motor vibration, shift of the building structures and a walking person. It is necessary to monitor not only the position but also to accurately distinguish a received signal. That means processing the frequency of the signal from a few Hz to hundreds kHz, or tens of MHz. Classification of individual frequencies must be very precise. Commonly used systems are not able to classify vibration without complicated postprocessing and thus measurement cannot be processed in real time [1], [2].

Distributed optic sensors can be described just like hundreds of sensors spread along optical fiber. Resolution of this measurement can be in micrometers or many kilometers. There are two types of sensors: short type or long type. Distributed optical sensors must send information not only about measurement but also about location of environmental effect. Disadvantage of optical sensors is their high price. Thanks to new development the price has been constantly decreasing during last years. In recent years, most optical sensors have used a combination of several sensing principles. Most commonly used are backscattered systems based on Rayleigh or Brillouin scattering combined with any interferometric method (Mach–Zehnder interferometer, Michelson interferometer) [3], [4], [7].

The article describes the simulation of three types of interferometers MZI (Mach–Zehnder interferometer), MI (Michelson interferometer) and SI (Sagnac interferometer) for simulation the VPIphotonics software was used. To simulate optical sensors no appropriate software has been developed yet. VPIphotonics is mainly used for simulation of data networks. Many optical elements are prepared as optical fibers, lasers, couplers. But their function does not correspond to measurement [7].

Physical phenomena causing the change of the refractive index in optical fiber can be described as [1]:

$$\Delta[\frac{1}{n^2}]_{ij} = p_{ijkl}e_{ij} \tag{1}$$

where p_{ijkl} are Pockels coefficients or components of photoelastic tensor and then $[\frac{1}{n^2}]_{ij}$ are constants of refractive index ellipsoid.

Photoelastic tensor has only two independent components, they are described as: p_{11} a p_{12} and then e_{33} is relative extension of the optical fiber. We can also calculate the relative change in refractive index for polarized transverse modes [1].

$$\Delta\Phi = knL\left\{e_{33} - \frac{n^2}{2}[(p_{11}+p_{12})e_{11} + p_{12}e_{33}]\right\}. \tag{2}$$

The sensitivity of optical fiber to the pressure can be described as [1]:

$$\frac{\Delta\Phi}{L\Delta p} = \frac{k_o n}{Y}(1-2\sigma)\left[1 - \frac{n^2(p_{11}-2p_{12})}{2}\right], \tag{3}$$

where Y is Young's modulos of the flexibility, σ is Poisson's coefficient, P_{ij} is material coefficient of the optical fiber.

The sensitivity of optical fiber to the temperature can be described as [1]:

$$\frac{\Delta\Phi}{L\Delta p} = k_o n\alpha_T + k_0\left(\frac{\theta n}{\theta T}\right)_p, \tag{4}$$

where α_T is linear temperature coefficient expansion of the material which the optical fiber is made of.

2 MACH-ZEHNDER INTERFEROMETER

MZI uses a DFB (Distributed Feedback Laser) light source module and two fiber couplers. On the output of the coupler there are two light beams that are coupled into a fiber. The influence of the environmental effect on the fiber is to induce an optical path-length difference between two light beams. The first arm of the MZI is used for measurement and the second one is used for reference. The phase difference between two arms is measured on the output of the MZI. [1], [7].

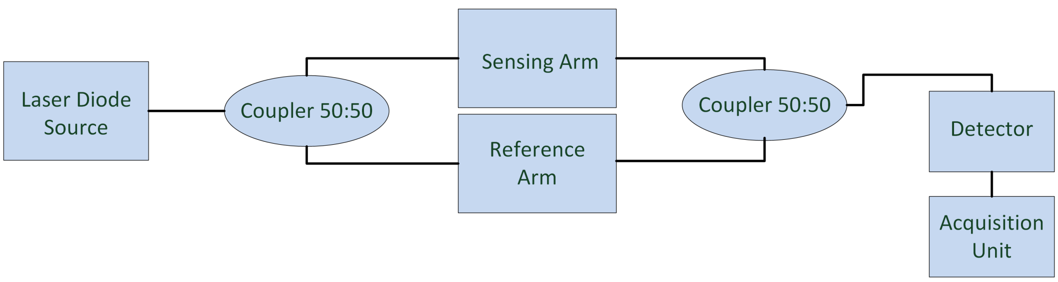

Figure 1: Block model of Mach-Zehnder interferometer

3 SIMULATION SETUP

Simulation in VPIphotonics software consists of two parts, the first part is transmission part which is made from DFB laser CW. Laser operates on wavelength of 1550 nm with power 3 mW and coherent length of 5 MHz. Light is coupled into two arms of interferometer and a signal is divided in ratio 50/50 by a coupler. Our testing optical path consists of 10 m optical fiber without amplifiers. We use commonly used optical fiber G.652.D. The route that is used for simulation simulates the actual effects that may arise on the optical fiber, it is mainly the dispersion and the Raman scattering. On one arm of the interferometer, time delay block which simulates vibration or temperature is inserted. In measurement influence of vibration is classified as a phase change difference between sensing and reference arm of the interferometer. Then the signal is merged in output coupler 50/50. The second part is a receiving part which consists of signal processing.

Basic parameters of simulation model:

- laser wavelength: 1550 nm,
- laser coherent length: 3 MHz,
- laser output power: 3 mW,
- couplers 50/50 with attenuation 3.3 dB,
- 10 m of optical fiber G.652D with attenuation 0.25 dB/km,
- power meter.

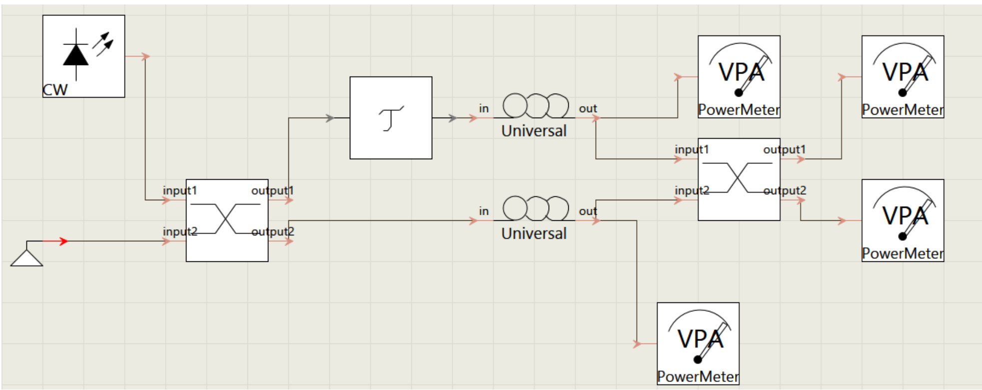

Figure 2: Simulation model of Mach-Zehnder interferometer in VPIphotonics

The simulation results show that the optical coupler used in the simulation does not work similarly as real coupler in measurement. The Couplers in VPIphotonics are set for use in telecommunication applications, not for optical sensing. The coupler only divides power from the laser [7]. If we measure output power on the arms of the first coupler in Figure 2 signal is divided 50/50 that mean 1.5 mW on each arm of the first coupler. On the output of the second coupler is signal merged from both arms to the one output arm of the MZI.

Output power of the first coupler:

- 1.5 mW,
- 1.5 mW,

and the second coupler:

- 0 mW,
- 1.1943 mW.

4 MEASUREMENT SETUP OF MZI

Our measurement model consists of laser diode Alcatel A-1905 LMI which works on wavelength 1550.75 nm with power 3 mW. Model also consists of two 50/50 optical couplers with attenuation 3.3 dB and 10 m of optical fiber G.652D. On the outputs of the couplers there are EXFO FPM-600 power meters. Basic parameters of measurement model:

- laser wavelength: 1550.75 nm,
- laser coherent length: 3 MHz,
- laser output power: 3 mW,
- couplers 50/50 with attenuation 3.3 dB,
- 10 m of optical fiber G.652D with attenuation 0.25 dB/km,
- power meter.

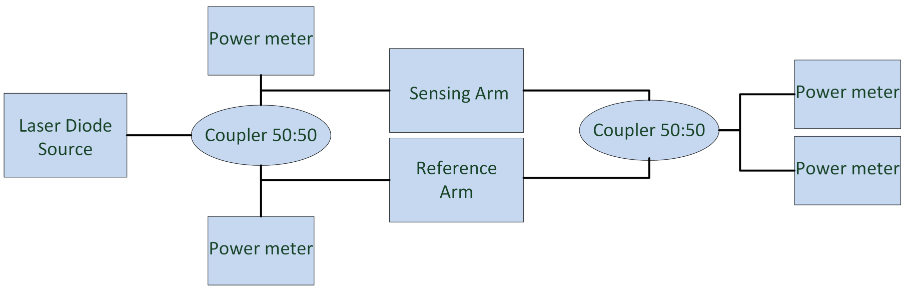

Figure 3: Measurent model of Mach-Zehnder interferometer

If we compare simulation and measurement model we can see differences in output power of the second coupler in both models. While manufacturing couplers, 10 % percent output power tolerance is taken into account. This fact confirms our measurement. If we measure power of the first coupler, output power is 1.476 mW, in simulation output power is 1.5 mW. On the output of the second coupler in simulation signal is merged from both arms to the one output arm of the MZI. That means that there is 0 mW on the first arm and 1.12 mW on the second arm. This is the ideal state of the Mach-Zehnder interferometer in VPIphotonics simulation software. [1] In the real measurement we are not able to do this, because both arms of the interferometer are influenced by phase change which is caused by physical effects on the interferometer. In measuring we are not able to provide the ideal condition for a reference fiber, it is constantly influenced by sensing fiber.

Output power of the first coupler:

- 1.476 mW,
- 1.484 mW,

and the second coupler:

- 0.14 mW,
- 0.68 mW.

5 CONCLUSION AND FUTURE WORK

The article showed simulation setup in VPIphotonics software which describes Mach-Zehnder interferometer. Simulation setup in VPIphotonics shows MZI and output power measurement. The further results of the simulation are compared with the measurement. The measurement results show that the simulation model of the interferometer does not match the tested model. The article also includes equations which describe the influence of vibration, temperature and other physical phenomena to optical fiber. The future work can be simulation and measurement of Michelson interferometer which confirms or disproves differences between simulation and measurement of another type of interferometer.

REFERENCES

[1] E. Udd, "Fiber optic sensors: an introduction for engineers and scientists, 2nd ed." *Hoboken: Wiley*. ISBN 978-0-470-12684-4. 2011.

[2] T. Zhu, Q. He, X. Xiao, X. Bao, "Modulated pulses based distributed vibration sensing with high frequency response and spatial resolution," *Optics Express*, vol. 21, no. 3, pp. 29–53. 2013.

[3] Y. Muanenda, C. Oton, S. Faralli, F. D. Pasquale, "A cost-effective distributed acoustic sensor using a commercial off-the-shelf DFB laser and direct detection phase–OTDR," *IEEE Photonics Journal*, vol. 8, no. 1, pp. 1–10, 2016.

[4] S. Huang, W. Lin, M. Tsai, M. Chen, "Fiber optic in-line distributed sensor for detection and localization of the pipeline leaks," *Sensors and Actuators*, vol. 135, no. 2, pp. 570–579. 2006.

[5] Y. Shi, H. Feng, "Distributed fiber sensing system with wide frequency response and accurate location," *IEEE Sensors Journal*, vol. 77, no. 3, pp. 219–224. August 2015.

[6] Herve C. Lefevre, "The fiber-optic gyroscope, 2nd ed." *USA: Artech House*. ISBN 16-080-7695-4. 2014.

[7] P. Münster, J. Vojtěch, T. Horváth, O. Havliš, P. Hanák, M. Čučka, M. Filka,"Simultaneous transmission of distributed sensors and data signals, " *In 39th International Conference on Telecommunications and Signal Processing*. ISBN 978-1-5090-1287- 9. 2016