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Measurement of Laser-Ultrasound using a Fiber Fabry-Perot Interferometer

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Abstract
This paper describes a non-contact scheme for laser-ultrasound measurement, in which a fiber Fabry-Perot interferometer is incorporated into the detection scheme. The fiber-based interferometer with proper protection is promising because of compact size and high immunity to external pertubations such as vibration and temperature change. The ultrasound measurement is conducted on a steel plate. The use of the intrinsic type fiber-based interferometer, in which the fiber itself is used as an interfering medium, is demonstrated on a condition that is applicable to the real field for the first time to our knowledge. In order to avoid the instability with respect to polarization state change in the fiber interferometer, a polarization maintaining fiber is employed. Clear ultrasonic signals are observed as a function of time in the output of the fiber interferometer.
Keywords: Laser ultrasound, fiber Fabry-Perot interferometer, polarization maintaining fiber (PMF), steel plate

1. Introduction

Laser-induced ultrasound has been one of the attractive candidates for non-contact inspection of material properties [1]. Non-contact nature of the technique has a major advantage of on-line measurement even in harsh and coarse environment, for example, hot rolling mill process in steel industry. In order to detect laser-induced ultrasound, several methods such as optical heterodyne interferometers [2], modified Sagnac interferometers [3], confocal Fabry-Perot interferometers (CFPIs) [4] have been introduced. CFPIs are especially attractive because they are immune to low-frequency fluctuation of the distance between the sample surface and the interferometer. Recently, another new type optical detection scheme employing a fiber Fabry-Perot interferometer (FFPI) was proposed [5]. In this paper, we design a detection scheme using the FFPI, and demonstrate a practical application of the proposed scheme to a steel plate for the first time to our knowledge. In order to avoid the instability with respect to the polarization state change in the fiber interferometer, a polarization maintaining fiber was employed. Based on the stability of light guidance in the polarization maintaining fiber (PMF) of the FFPI, a higher level of immunity and robustness to low-frequency ambient vibration and temperature fluctuation compared to conventional detection is expected. We expect that our results will be useful for technical development to know metallurgical properties such as average grain size in steel industry.

2. Detection scheme using a fiber Fabry-Perot interferometer

Figure 1 shows the detection scheme using the FFPI in our experiment. In this case, backscattered light from the sample surface is incident on the FFPI. Direct coupling from the air to the PMF of the FFPI was not used because the optical alignment for the direct coupling scheme is very sensitive to ambient temperature change and vibration. A multi-mode fiber (MMF) to 1300 nm single-mode fiber (SMF) coupler is inserted in front of the SMF for gradual and stable coupling. The light propagates from the MMF to the SMF, and goes out of the SMF. The light in the air passes through the collimator and the polarization beam splitter (PBS) that divides the light according to the polarization state for use of one polarization mode so that the polarization change does not affect the detection performance. The quarter waveplate after the PBS changes the polarization state of the light to the circularly polarized one. Next to the quarter waveplate, the light is focused by the 8 mm focal lens, and launched into the core of the PMF as the input light. Here, the PMF used as a Fabry-Perot cavity of the FFPI is gold-coated on both ends with 95% reflectivity. In this case, the reflected light of the PMF comes out of the PBS in 90º vertical direction to the input light since the reflected light has the orthogonal linear polarization state to the input light by double-pass through the quarter waveplate, which separates the input and the reflected light. The reflected mode is used as output signal of the FFPI containing information of the laser-induced ultrasound. A part of the PMF is wound and attached on the piezoelectric transducer (PZT) in order to control the cavity length by applying the electrical signal to the PZT.

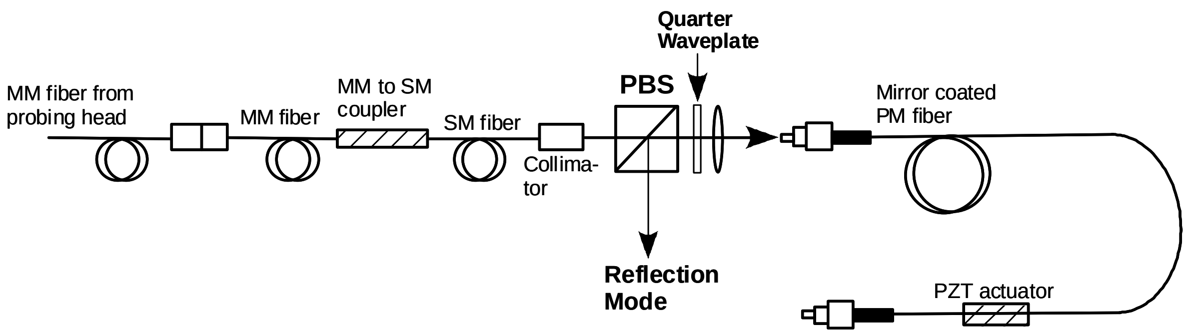

Figure 1. Detection scheme using a fiber Fabry-Perot interferometer

The most important property of the scheme to determine the system performance is the coupling efficiency of the light from the air to the PMF. The coupling efficiency of the FFPI is expected to be lower than that of the CFPIs because the light has to be launched into smaller core region (about 3.4 μm diameter) of the PMF in the FFPI. The coupling loss of the scheme is caused by two effects as follows. Firstly, the incident light is launched into guided modes of the MMF from the air. In this case, only the LP01 mode is used for ultrasound detection because the PMF just supports the LP01 mode as a guided mode in the core for stable performance of the FFPI. Therefore, the light of higher-order modes is absorbed in the jacket surrounding the PMF or reflected on the input end of the PMF and radiates to the air without propagation in the core region. Therefore, the portion of the higher order modes is regarded as the coupling loss. The other source that causes the coupling loss is the transmission loss of the LP01 mode. Therefore, total coupling loss is written as follows.

Total coupling loss = the launched portion of higher-order modes + the transmission loss of the LP01 mode

The amount of the launched portion of the LP01 mode mainly depends on sample surface condition. It means that the power of higher-order modes is reduced when the surface condition is changed to mirror-like one. The transmission loss of the LP01 mode depends on whether the two mode fields and the numerical apertures (NAs) match with each other at the boundary of two different fibers such as the MMF – the SMF and the SMF – the PMF. In order to match the two mode fields and the NAs, adequate lenses were used at the connection point between the MMF – the SMF, and the SMF – the PMF. In the experiment, the transmission loss of the LP01 mode was minimized.

Figure 2 depicts the experiment for evaluation of the coupling efficiency from the air to PMF. Firstly, we used the 532 nm laser to directly launch the LP01 mode from the laser to the MMF without any medium, and adjusted the fibers and lenses. The maximum achievable value of the LP01 transmission was more than 70%. Next, we inserted a steel plate sample obtained in hot-rolling mill process so that the light from the detection laser is reflected on the sample surface, and launched into the MMF by collecting lens. The resultant coupling efficiency was about 3.4%, from which it is noted that only about 5% of the reflected light on the sample surface was launched into the LP01 mode of the MMF. The value will be varied with sample surface conditions.

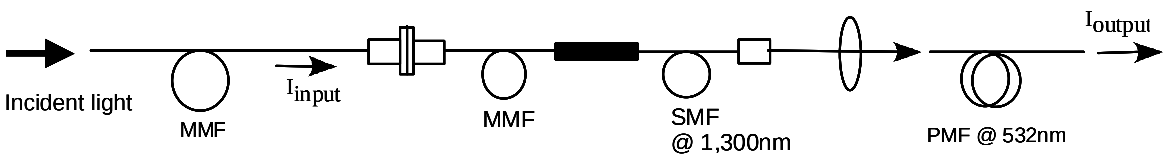

Figure 2. Evaluation of coupling efficiency from MMF to PMF

3. Experimental results for measurement of laser-ultrasound using proposed detection scheme

We constructed the whole experimental setup as shown in figure 3 for generation and detection of ultrasound employing the FFPI described in the previous section to measure the ultrasound signal. Pulsed laser beams from Q-switched Nd:YAG pulsed laser (Brilliant B, Quantel corp.) for ultrasound generation are incident on the target surface via bulk-optic alignment. A hot rolled steel plate (width, length, thickness: 3 cm, 4 cm, 10 mm) is used for the target that is placed in the vacuum chamber with the induction heater in order to conduct the experiment with changing the temperature. The laser pulse can be incident on the front or the back side of the target by changing the optical alignment. Continuous wave laser beam from 532 nm single frequency laser (NPRO 142, JDSU corp.) is also applied to the same position of the sample surface at which the generation laser pulse hits. The backscattered light is launched into the MMF by the collection head, and enters the FFPI.

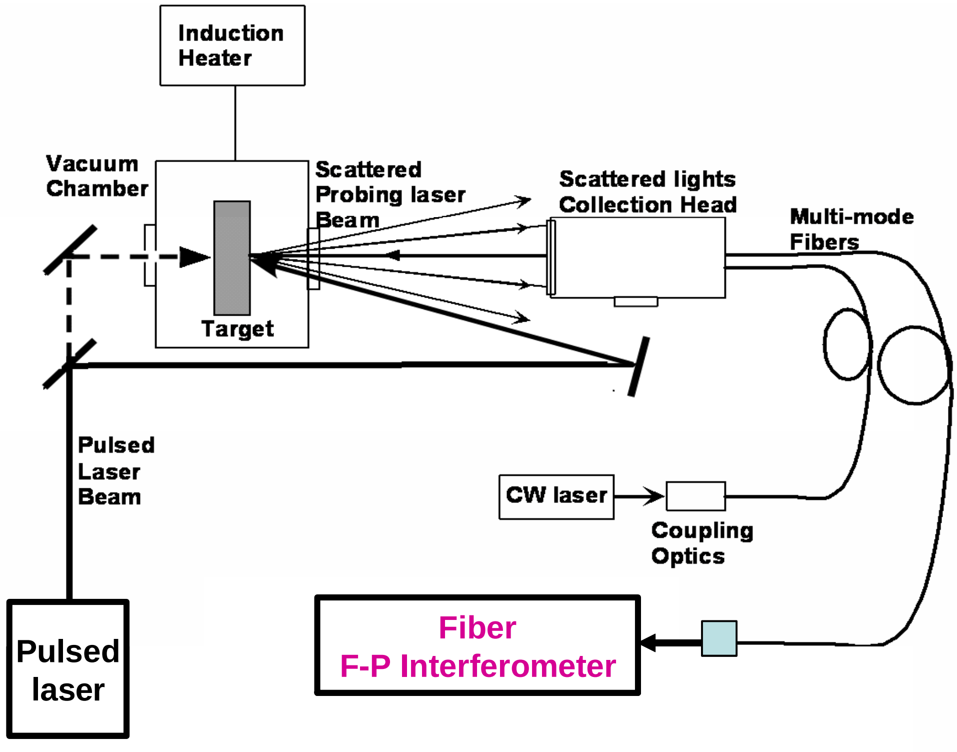

Figure 3. Experimental setup for generation and detection of laser-ultrasound

Figure 4 shows the experimental results of the reflection fringe patterns of the FFPI with a 3 m long cavity and ultrasonic signals measured by the FFPI. Clear fringe patterns of the FFPI are observed in Figure 4 (a). Figure 4 (b) shows detected ultrasonic signal of longitudinal wave echoes for a front incident generation laser pulse in the ablation condition and detection laser with 500 mW at room temperature. The calculated velocity of the longitudinal wave from the time delay of 3.35±0.03 μsec between two adjacent peaks in figure 4 (b) and the sample thickness of 10 mm is about 5970±50 m/s, whose accuracy can be improved by appropriate signal processing such as noise filtering and zero-crossing method.

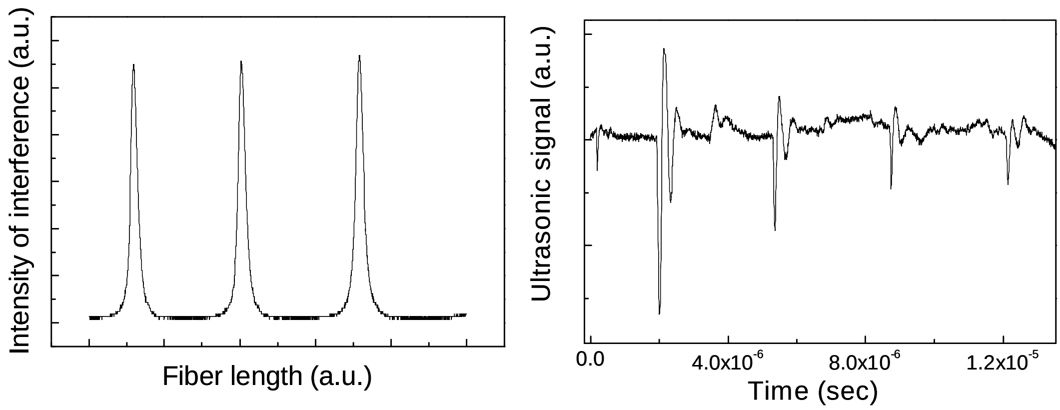

Figure 4. (a) fringe pattern of FFPI and (b) ultrasonic signals measured by FFPI with 3 m cavity length

4. Conclusions

The untrasound measurement is conducted on a steel plate. The use of the intrinsic type fiber-based interferometer, in which the fiber itself is used as an interfering medium, is on a condition that is applicable to the real field for the first time to our knowledge. In order to avoid the instability with respect to the polarization state change in the fiber interferometer, a polarization maintaining fiber is employed. Clear ultrasonic signals of longitudinal wave echoes in the ablation condition are observed as a function of time in the output of the fiber interferometer. The calculated velocity is 5970±50 m/s, whose accuracy can be improved by proper signal processing such as noise filtering and zero-crossing method. We expect that our results will be useful for technical development to know metallurgical properties such as average grain size in steel industry.

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