Fiber Fabry-Perot cavity microphone and its application to monitoring laser cutting

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Abstract. Fiber Fabry-Perot cavity microphone has attracted much attention due to some outstanding advantages of high sensitivity, small probe, resistance to electromagnetic wave, etc. In this paper, we reported fiber Fabry-Perot cavity microphone with a high sensitivity of more than 200mV/Pa and high thermal stability in the temperature range from -20°C to 60°C. Furthermore, the fiber Fabry-Perot cavity microphone was firstly used to monitor laser cutting by laser-induced sound. By employing the fiber Fabry-Perot cavity microphone, we can precisely control the laser processing time by laser-induced sound. This is of great benefit to saving time for mass production.

1. Introduction
With developing of fiber technology and fiber sensing technology, fiber optic microphone has become a hot research because it has many advantages of high sensitivity, resistance to electromagnetic wave, low transport loss, etc. So fiber microphones based on different principle and different structure have been developed, such as reflective intensity [1, 2], fiber Bragg grating [3, 4], fiber Michelson interferometer [5, 6], fiber Mach-Zender interferometer [7, 8], fiber Sagnac interferometer [9, 10], and fiber Fabry-Perot interferometer [11-14]. Among them, fiber Fabry-Perot cavity microphone is a star because of simple structure. Normally, it consists of a fiber and a membrane. The fiber propagates both incident light and reflective light. So the probe of fiber Fabry-Perot cavity microphone is small. Fiber Fabry-Perot cavity microphones with high sensitivity and small probe could have various applications, for example, monitoring laser cutting.

Laser manufacturing technology has many unique advantages, such as good processing flexibility, high production efficiency, easy to realize intelligent processing, etc. It is a complex physical and chemical process. There may be various defects and errors in the process. In order to improve the reliability of laser manufacturing, it is necessary to monitor the laser manufacturing process [15-18].

In the process of laser manufacturing, several of signals will be produced, such as laser-induced sound, ultraviolet radiation, visible light, infrared radiation and plasma. These signals can be used to monitor laser processing. Among them, the laser-induced sound has characters of large intensity, easy detection, insensitivity to loading direction and working distance, and non-contact measurement. Therefore, the monitoring of laser manufacturing process based on laser-induced sound is a suitable technology [19-21].
In this paper, we reported a fiber Fabry-Perot cavity microphone that has high sensitivity and high thermal stability. And a preliminary experiment on laser drilling monitoring is carried out by using a self-made fiber Fabry-Perot cavity microphone firstly.

2. Fiber Fabry-Perot cavity microphone

Figure 1(a) shows a typical fiber Fabry-Perot cavity microphone. The probe size is 1/2 inch. The fiber Fabry-Perot cavity consists of end face of single mode fiber and a super thin metal membrane. The self-made fiber Fabry-Perot cavity microphone has high sensitivity and high thermal stability, which is benefit to application.

Figure 1(b) shows the sensitivity curve of a typical fiber Fabry-Perot cavity microphone. The sensitivity is very high of more than 200mV/Pa. And frequency response is almost flat with small fluctuation in the frequency range of 50Hz-6.3kHz.

To investigate the thermal stability of fiber Fabry-Perot cavity microphone, the probe was put into a temperature tank, and the output response of the fiber microphone for 1kHz sound wave was recorded every 20°C from -20°C to 60°C. A condenser microphone is used as a reference. Figure 2 shows the experimental result. The large and blue curve in figure 2 is the output of the fiber Fabry-Perot cavity microphone, and the small and black curve is that of the condenser microphone. The experimental data clearly shows that the fiber Fabry-Perot cavity microphone can work well when the temperature is changed. This result indicates that the fiber Fabry-Perot cavity microphone has a high thermal stability, which is obviously better than those reported in literatures [11, 13-14].

Figure 2. Output of fiber Fabry-Perot cavity microphone (large and blue signal) at different temperature for 1kHz sound. Small and black signal is output of condenser microphone for reference.
To employ the sensitivity at temperature of 20°C as reference, we can obtain that the relative change of sensitivity is 9.2% in the temperature range of -20°C to 60°C, which is acceptable in engineering application.

3. Experiments on monitoring laser cutting

3.1. Experimental details
Figure 3 shows the experiment of sound monitoring on laser cutting. A fiber Fabry-Perot cavity microphone probe is fixed on the steel bracket by a strong magnet. So the probe can be fixed flexibly according to practical situation. In the experiment, the distance between probe and specimen is about 1m. When laser is interacting with the specimen, laser can produce sound wave. The laser-induced sound can be detected by the fiber Fabry-Perot cavity microphone.

![Figure 3. Experimental setup for monitoring laser cutting by fiber Fabry-Perot cavity microphone.](image)

3.2. Experimental results

3.2.1. Counting of holes.
For laser cutting, hole is an important object. On many machine elements, there are lots of holes. And laser cutting is an important and effective processing method of drilling hole. But the quality of the holes could be affected by laser cutting process. So it is very necessary to monitor the process of drilling hole.

To verify the validity of sound monitoring of drilling hole by fiber Fabry-Perot cavity microphone, hole counting experiments were conducted. In these experiments, the parameters were empirical. First, one hole was drilled on the specimen. Then a set of experiments that drilled 2, 4, 5, 8, and 10 holes were processed. Figure 4 shows the laser-induced sound of drilling holes.
As can be seen from figure 4(a), a pulse emerged when one hole was produced. When the number of holes was increased, the sound signal became comb-like. From figure 4, it is obvious to find that the number of the comb pulses is the same as the number of the drilled holes. It can also be obtained that the processing time for drilling 10 holes is only about 400ms. So the average time of each hole drilling is 40ms, which is not distinguishable by human ear.

It is worth noting that the laser-induced sound signal has high signal-to-noise ratio, which is of great advantage for controlling hole drilling. Therefore, the number of holes in the laser cutting can be identified reliably and accurately by using the fiber Fabry-Perot cavity microphone.

3.2.2. Accurately controlling of hole drilling.

On the basis of reliably identifying the hole number, accurate hole drilling can be further realized, that is, after perforation hole is formed, it begins to fabricate the next hole. In this way, it can not only save time and cost, but also avoid the damage caused by surplus energy to the formed perforation holes. So
this can get holes with better quality by accurate control, which is of great significance for the production of aero engine blades.

Therefore, we first set up the time of each hole drilling based on experience. Then we gave the controlled time of drilling each hole through analyzing the collected sound signals. The experimental data is shown in Figure 5.

Figure 5 Sound signal of 4 hole drilling at the working period of laser pulse of 70ms (a, b) and 10ms (c, d).

Figure 5(a) shows the collecting acoustic wave for drilling 4 holes when the laser pulse period was set to 70ms. It is clear to find 4 pulses corresponding to 4 holes. To enlarge the first two pulses in figure 5(a) marked by a red dot-line rectangle, as shown in figure 5(b), we can see that the time interval between the first pulse front and the second pulse is about 70ms, which is the same as the laser pulse period. From figure 5(b), it is especially important to note that there is only strong sound signal in the period of about 10ms before in this 70ms cycle. After that, the laser-induced sound is not detected before the rising edge of the next pulse. It can infer that the through-hole is formed during this 10ms. In the later 60ms, no material interacts with laser and no notable sound signal is produced.

So it can be determined whether the through-hole is formed by laser-induced sound signal. And we can set more reasonable period for drilling hole by laser. According to figure 5(b), we set the working period to 10ms without changing other parameters, such as laser power, radius of hole. And a controlled experiment was conducted. The experiment result is shown in figure 5(c). Figure 5(c) and figure 5(a) have the same time axis scale. And from figure 5(c), the number of pulse almost cannot be recognized. Figure 5(d) shows the enlarged pulse that marked by a red dot-line rectangle in figure 5(c). From figure 5(d), it can clearly see four pulses without overlapping each other. This means that four through-holes are well formed.

Therefore, we can precisely control the processing time by laser-induced sound. This has of great benefit to saving time. As shown in figure 5, it costs 280ms for cutting 4 holes by experience, while it...
only costs 40ms for cutting the same 4 holes by sound monitoring. This greatly reduces the processing time, which is of great significance for mass production.

4. Conclusion
A fiber Fabry-Perot cavity microphone with sensitivity of more than 200mV/Pa and high thermal stability is reported. The relative change of sensitivity of the fiber microphone is 9.2% in the temperature range of -20°C to 60°C. The fiber Fabry-Perot cavity microphone may be suitable for various applications.

By employing self-made fiber Fabry-Perot cavity microphone, a monitoring experiment on laser drilling hole has been conducted. It is the first time that fiber Fabry-Perot cavity microphone was used to monitor laser cutting. Experimental result shows that the processing time can be precisely controlled so that the efficiency can be greatly improved for mass production. It exhibits a good prospect of fiber Fabry-Perot cavity microphone for application to monitor laser manufacturing.

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References
[1] Li R, Madamopoulos N and Xiao W 2010 Appl. Opt. 49 6660-67.
[2] Song J and Lee S 2006 Microwave Opt. Technol. Lett. 48 1833–36.
[3] Bandutunga C P, Fleddermann R, Gray M B, Close J D and Chow J H 2016 Appl. Opt. 55 5570-74.
[4] Zheng D, Liu Q and Li E 2009 Proc. SPIE 7157 71570U.
[5] Liu L, Lu P, Liao H, Wang S, Yang W, Liu D and Zhang J 2016 IEEE Sensors J. 16 3054-58.
[6] Breguet J, Pellaux J P and Gisin N 1995 Sen. and Actuat. A 48 29-35.
[7] Li Q, Wang H, Li L, Liang S and Zhong X 2015 Infra. Laser Eng. 44 205-9.
[8] Abuelma'atti M T 2011 Appl. Acoust. 72 305-9.
[9] Udd E 1983 Proc. SPIE 425 90–5.
[10] Ma J, Yu Y and Jin W 2015 Opt. Exp. 23 29268-78.
[11] Mao X, Yuan S and Zheng P 2017 J. Lightwave Technol. 35 2311-4.
[12] Zhang W, Wang R. and Rong Q 2017 IEEE Photon. J. 9 7103208.
[13] Chen J, Li W, Jiang H and Li Z 2013 Optik 124 339-42.
[14] Wang Q and Ma Z 2013 Opt. Laser Technol. 51 43-6.
[15] Schleier M, Adelmann B, Neumeier B and Hellmann R 2017 Opt. Laser Technol. 96 13–17.
[16] Adelmann B, Schleier M, Neumeier B and Hellmann R 2016 Appl. Opt. 55 1772–78.
[17] Wen P, Zhang Y and Chen W 2012 J. Laser Appl. 24 032006.
[18] Schleier M, Adelmann B, Esen C and Hellmann R 2018 IEEE SENSORS J. 18 1585-90.
[19] Liu J, Chen Y and Xu Q 2006 Trans. China Welding Instit. 27 72-5.
[20] Gu H and Duley W W 1996 J. Phys. D 29 556-60.
[21] Farson D, Hillsley K, Sames J 1994 Proc. SPIE 2500 86.