Chapter 5. Conclusion and Future Work

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5.1 Conclusions

To fulfill the objective of providing reliable fiber optical pressure sensors capable of operating in engine, minimizing the sensor size and realizing batch fabrication of the pressure sensors, this thesis presents the detailed research work on the design, fabrication and measurement of diaphragm-based fiber optic pressure sensors.

Based on the EFPI principle, the diaphragm-based pressure sensing technique was designed, developed and evaluated. Static pressure, dynamic pressure and the temperature dependence of the sensors were measured. These measurement results indicate that this type of sensor is a good candidate for high temperature (600°C) environment.

MEMS techniques, such as wet chemical etching and thin film deposit, were successfully combined and used in the diaphragm fabrication process. Especially, these techniques were implemented on the fused silica diaphragms instead of silicon wafers. About twenty pits could be fabricated in the same process. The total time used on photolithography process and wet etching on a diaphragm can be as short as one hour. The patterns transferred onto the fused silica diaphragms are uniform, with smooth surface and great depth that suffice the requirements of the pressure sensor application. It is revealed that wet etching process is a repeatable, cost effective and reliable technique.

Sol-gel process is used in the sensor fabrication in order to bond the diaphragm with the ferrule and the ferrule with the fiber. This is a good start point that new materials can be used in the fiber optic sensor fabrication.

Besides the fabrication of the sensor head, this thesis evaluates the SCIIB system. The experimental testing showed that SCIIB system can provide self-calibrating capabilities with potential high frequency response measurement.
5.2 Future Work
There are also a lot of potentials that the sensor head and testing system are improved in the future.

For sensor fabrication, the temperature dependence can be further improved by using low-temperature, direct bonding technology. Right now, fused silica wafer-to-wafer bonding can be realized by using high quality fused silica diaphragms in clean room. But fused silica wafer-to-patterned-wafer bonding, and ferrule-to-patterned-wafer bonding are still a problem for us. Because after chromium layer coating, and the photolithography process, the surface quality of the patterned wafer cannot meet surface requirements of direct bonding. The surface roughness of patterned wafer is around 40nm while the direct bonding requirement is less than 5nm. So more experiments or new ideas are needed for direct bonding.

One of the main advantages of MEMS in fabrication is MEMS processes can realize batch fabrication of pressure sensors. Though we need to design, develop or purchase more equipment, such as aligner, dicing saw, bonder, batch fabrication and mass production of fiber optic sensors should be very promising. Wet chemical etch is the first step of batch fabrication. On one 1x1 inch fused silica diaphragm, at least 25 etched pits can be generated in one process. And this process can only cost about 1 and half hour to finish. Ferrule polish, ferrule-to-wafer bonding can also be done by using special designed holders in the future.

In addition, gold coating on both diaphragm and fiber head can be conducted to improve signal to noise ratio by increasing the reflection coefficient. Normally, without coating, the reflection coefficient from both sides of the interference cavity is about 4%. With proper coating, the reflectance can reach as high as 90%.

For sensor testing, we still don’t have an effective measurement system to measure the frequency response of the pressure sensor. The frequency response of our sensor is designed to test pressure signal with 150kHz. The sampling rate of SCIIB digital signal processing is above 100kHz. Among the factors that affecting dynamic pressure measurement, only the high frequency, high amplitude pressure signal
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generator is needed. Through the research, we found that impulse response of a sensor can be the alternative way to measure the frequency response of the sensor.

A shockwave generator can generate impulse waves. All shockwave generators are based on the geometric principle of an ellipse. Shock waves are created at the first focal point (F1) of an ellipsoid and are directed to the second focal point (F2). The focal zone is the area at F2 where the shockwave is concentrated. There are three different types of shock wave generators: Electrohydraulic, piezoelectric, and electromagnetic generator. [28][29]

**Electrohydraulic generator**: This is the most commonly employed method of shockwave generation. It uses the tips of an electrode as a point source. The electrode is placed in the first focal point F1 of an ellipsoid. An electrical discharge of a high-voltage current occurs across a spark-gap electrode located within a water-filled container. This discharge results in a vaporization bubble, which expands and immediately collapses, generating a high-energy pressure wave. The spherical shock waves are reflected by a metal ellipsoid and focused into the second focal point F2.

**Electromagnetic generator**: There are two constructions. One is to use a cylindrical source and the other one is to use point source. For the structure using a cylindrical source, an electrical current is applied to an electromagnetic coil mounted within a water-filled cylinder. The high current pulse forms a cylinder shaped pressure wave, which is reflected by a hyperbole shaped metal reflector to achieve focusing. For point source, the system uses an electromagnetic coil and a metal membrane opposite to it. A high current pulse is released through the coil generating a strong magnetic field, which causes the metallic membrane to be repelled, resulting in extremely rapid movement of the membrane, which produces a shaped shock wave. To focus the wave, an acoustic lens is used. The focal point is defined by the focal length of the lens.

**Piezoelectric generator**: Hundreds-to-Thousands of ceramic or piezoelectric crystals are mounted to a spherical surface and set in a water-filled container. When switching a high voltage pulse to the crystals, they immediately contact and expand, generating a low pressure pulse in the surrounding water. This system is self focusing by the shape of the sphere.

The shock wave of the electromagnetic generator has rise time of 5.3 ns, maximum pressure of 31.9MPa (4,657psi), and the duration of the positive pressure phase of
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3.73\mu s.\textsuperscript{[25]} By using this type of high frequency pressure generator, we can test the frequency response of our pressure sensors in the future.