# Sagnac Interferometer with Phase Bias Enhancement by 3x3 Fiber Coupler for Airborne Ultrasound Detection

Zijian Wang[1†], and Kentaro Nakamura[1*]
([1]Laboratory for Future Interdisciplinary Research of Science and Technology, Institute of Innovative Research, Tokyo Institute of Technology)

## 1. Introduction

Airborne ultrasound is emerging as a crucial technology for proximity sensing in vehicles and drones. Simultaneously, high-intensity aerial ultrasound is gaining attention for its applications in haptic devices [1)], non-contact manipulation of small objects [2)], and material evaluation without physical contact [3)]. As new airborne ultrasonic methods are developed, the need for precise measurement of ultrasonic sound pressure is becoming increasingly important. A fiber optic probe based on changes in optical reflectivity [4)] has been utilized for this purpose. Interferometric methods detecting the refractive index modulation of the air due to sound pressure have also been explored by several groups [5)] due to their higher sensitivity compared to the fiber optic reflectivity approach. Among these, a greater practical value of Sagnac interferometer has been demonstrated from the view point of its ability to eliminate low frequency disturbances [6)].

We explained and verified in detail the working principle and characteristics of the fiber optic Sagnac ultrasound sensing system and demonstrated the effect of the initial phase bias on the system responsivity utilizing an electro-optical modulator [7)]. In this report, we present a Sagnac interferometer utilizing a 3x3 fiber coupler which provides a phase bias of up to 120 ° for detecting refractive index modulation induced by acoustic fields, and greatly improves the sensitivity with ensuring the minimal configuration.

## 2. System Configuration Overview

A fiber-optic Sagnac interferometer shown in **Fig. 1** is studied. A fiber coil made of a standard single-mode fiber (length of 1000 m, compatible with SMF-28) is used as a Sagnac delay coil. An amplified spontaneous emission (ASE) light source (ASE-FL7004, 1530-1610 nm, 20.46 mW, FIBERLABS) and an integrated photo receiver (2053-FC-M, NEWPORT) were used in the experiments. The ASE light source and optical receiver are connected to the B1 and C1 port of the 3x3 fiber coupler (SMFC-3X3-1560, 1560 ± 30 nm, 33:33:33 Split, FC/APC, Sichuan lightsos optoelectronic technology Co., LTD), the delay coil and air gap are connected to the A2 and C2 port.

Two fiber ports (PAF2A-7C, FC/APC, $F$ =7.5 mm, THORLABS) were used to create an air gap of 45 mm, which is introduced in one end of the fiber coil and works as an acoustically sensitive part. Angled cuts were applied to the air gap to minimize the reflection. Difficulty in spatial adjustment caused a transmission loss of around 5.4 dB across the air gap.

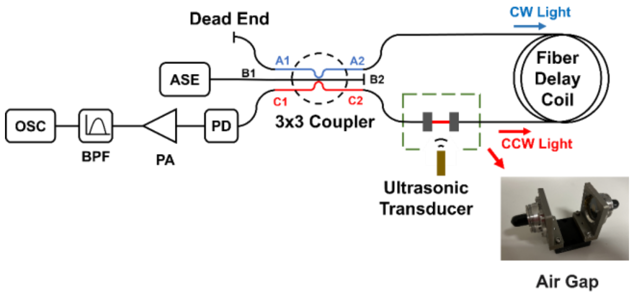


Fig. 1. Sound pressure detection using fiber-optic Sagnac interferometer with 3x3 fiber coupler. ASE, amplified spontaneous emission; PD, photodetector; PA, pri-amplifier; BPF, bandpass filter; OSC, oscilloscope.

## 3. Phase difference between 3x3 fiber coupler ports and Initial phase bias effects

Due to the coupling characteristics of the 3x3 fiber coupler, when light is input at one port, the phases at the three output ports differ by 120 degrees relative to each other. As shown in Fig. 1, the clockwise (CW) light travels through paths B1-AX (+ 120°) and C2-C1 (0°) before reaching the photodetector (PD), accumulating a total phase difference of 120 degrees. Meanwhile, the counterclockwise (CCW) light travels through paths B1-C2 (- 120°) and A2-C1 (+ 120°) before reaching the PD, resulting in a total phase difference of 0 degrees. Thus, there is an initial phase bias of 120 degrees between the CW and CCW light during the interference process.

**Fig. 2** shows the optical interference as a function of the phase. The magnitude of the initial phase bias determines the position of the ultrasonic modulation operating point, while its slope on the interference curve dictates the initial responsivity and the linear dynamic range of ultrasonic detection.

E-mail: †zwang@sonic.pi.titech.ac.jp, *knakamur@sonic.pi.titech.ac.jp

When the initial phase bias is close to or equal to zero, the system's initial responsivity approaches zero. Because the 3x3 fiber coupler provides a 120-degree phase bias, the system exhibits significantly superior responsivity and linear dynamic range compared to the 2x2 fiber coupler system.

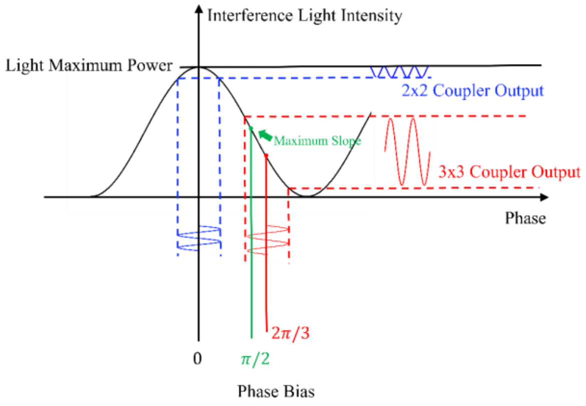


Fig. 2. The optical interference caused by the ultrasonic modulation based on 2x2 and 3x3 fiber couplers.

### 4. Sensor signal amplitude and sound pressure

We compared the output signals of the Sagnac interferometric systems based on 2x2 and 3x3 fiber couplers, respectively. Two bolt-clamped Langevin transducers were driven at its fundamental frequency of 29.0 kHz and 60.7 kHz. A 1/8-inch condenser microphone (Type 7118, ACO) was used to measure the sound pressure and verify the characteristics of the sensing system.

As **Fig.3** demonstrates, the output signal levels of the 2x2 and 3x3 fiber coupler systems at 29.0 kHz were 0.0023 mV/Pa and 0.56 mV/Pa, respectively. The difference reached up to 47.7 dB.

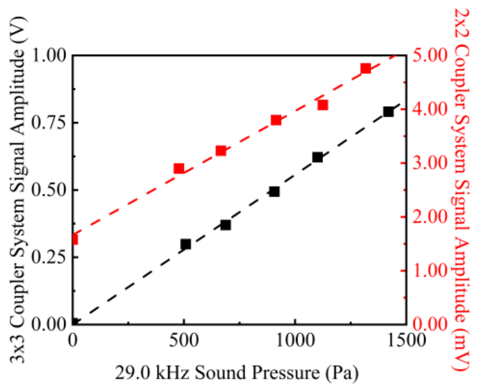


Fig. 3. The responsivity of the 2x2 and 3x3 fiber coupler systems at 29.0 kHz.

As **Fig.4** shows, the output signal levels of the 2x2 and 3x3 fiber coupler systems at 60.7 kHz were 0.0043 mV/Pa and 1.19 mV/Pa, respectively. The difference was up to 48.3 dB.

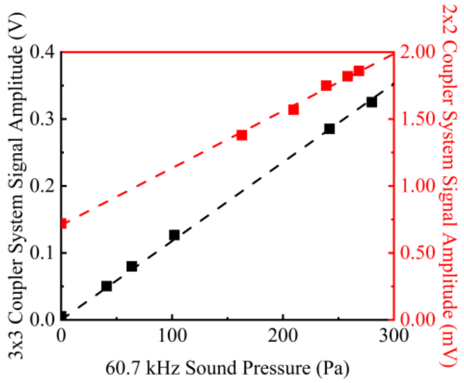


Fig. 4. The responsivity of the 2x2 and 3x3 fiber coupler systems at 60.7 kHz.

Due to the high responsivity of the 3x3 fiber coupler system, the impact of noise-induced offset is minimal. The responsivity for both 2x2 and 3x3 fiber coupler systems at 60.7 kHz is superior to that at 29.0 kHz, which is consistent with the matching relationship between Sagnac interferometer coil length and ultrasonic frequency.

### 4. Conclusion

Ultrasonic sensor based on fiber-based Sagnac interferometer with a simple design was constructed using a 3x3 fiber coupler. The setup exhibited significantly superior response and signal-to-noise ratio at ultrasonic frequencies of 29.0 kHz and 60.7 kHz compared to a similar system utilizing a 2x2 fiber coupler. The improved performance is attributed to the large initial phase bias introduced by the 3x3 coupler.

The system eliminates the need for precise and costly optical components. Additionally, the sensitivity of the system is comparable to that of commercial condenser microphones, indicating substantial potential for practical applications.

### References

1) M. Kunita, Electron. Commun. Jpn 90, 9–19 (2007).
2) T. Hoshi, et al., IEEE Trans. on Haptics, 3, 3, pp.155-165, 2010.
3) R. Nakamura, Y. Mizuno, K. Nakamura, Jpn. J. Appl. Phys., 52, 7, pp. 07HE02-1 – 07HE02-4, 2013.
4) Hao Yang, et al., Photon. Res. 11, 1139-1147, 2023
5) H. Takei, T. Hasegawa, K. Nakamura, and S. Ueha, Jpn. J. Appl. Phys. 46, 7S, pp. 4555-4558, 2007.
6) Fomitchov, P. A., Sridhar Krishnaswamy, and J. D. Achenbach. Optics & Laser Technology 29.6: 333-338, 1997.
7) Wang Z, Mizuno Y, Nakamura K. Journal of Lightwave Technology, To be published in 2024.