Optical Fiber Artificial Neuromast for Versatile Underwater Safe Navigation

Liangye Li[1], Xuhao Fan[2], Shunfeng Sheng[1], Yunfei Liu[1], Wangyang Xu[1], Wei Xiong[2], and Qizhen Sun[1*]
[1]*School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, Hubei, P. R. China*
[2]*Wuhan National Laboratory for Optoelectronics, Wuhan 430074, Hubei, P. R. China.*
**E-mail address: qzsun@mail.hust.edu.cn*

Abstract: We present an optical fiber artificial neuromast inspired by fish lateral lines for versatile underwater safe navigation, exhibiting an ultra-high flow sensitivity of 62.02 nm s/mL (0-0.05mL/s) and a resolution of 0.32 μL/s. © 2022 The Author(s)

1. Introduction

Underwater vehicles play a vital role in marine scientific research, exploration, and military, while water velocity and water disturbance are important environmental factors that affect underwater forewarning, creature tracking, and environmental considerations, which are closely related to the safety of underwater vehicles. By determining the flow velocity and disturbance, appropriate adjustments to the current working state of the vehicle can be made. However, traditional underwater turbine flowmeters, ultrasonic flowmeters, and microelectromechanical systems (MEMS) still face challenges with corrosion, large size, low sensitivity, complex settings, and the need for external power supplies [1]. Thus, the design of underwater sensors with compact size and high sensitivity still remains a challenge. Optical fiber sensors based on Fiber Bragg Gratings (FBGs) [2], and Fabry-Perot interferometer (FPI) [3] present excellent performance in anti-corrosion, and electromagnetic insulation, but they usually suffer from low sensitivity. Therefore, developing a highly sensitive, compact underwater sensor with the ability to resist electromagnetic interference is urgent for the safety of underwater vehicle navigation.

In this paper, we propose a compact optical fiber artificial neuromast inspired by fish lateral lines for versatile underwater safe navigation. The flow velocity signal is monitored by the optical wavelength while the water disturbance is detected by the optical intensity. The artificial neuromast exhibits a high flow velocity sensitivity of 62.02 nm s/mL with R^2 higher than 0.99, a velocity resolution of 0.32 μL/s, and a sensor measurement range of 0-0.05 mL/s. In addition, water disturbance could be clearly detected by power variation, which indicates excellent forewarning.

2. Working Principle and Fabrication

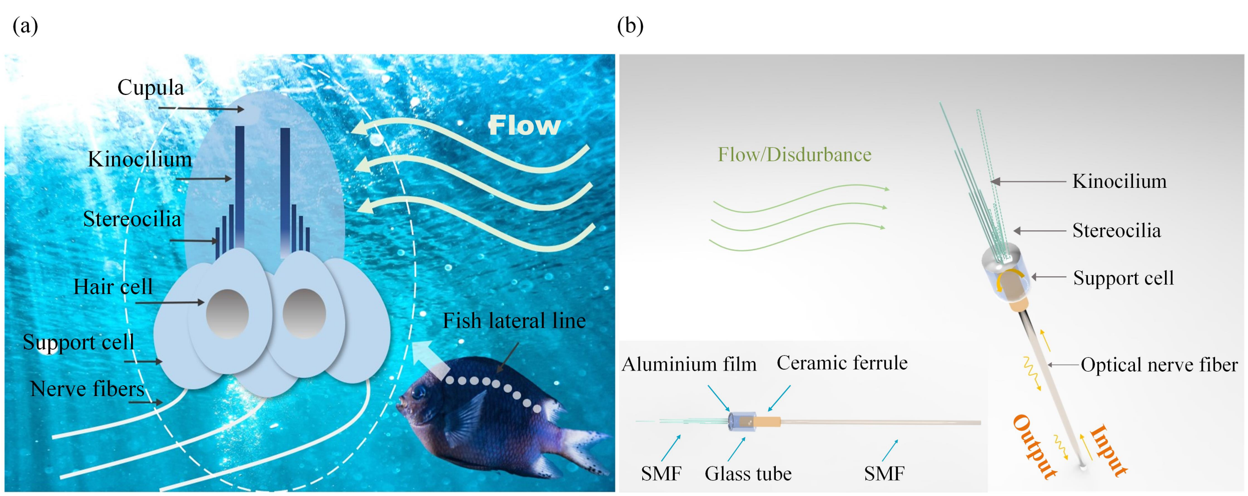

Fig. 1. (a) Schematic diagram of a fish's neuromast. (b) The structure of optical fiber artificial neuromast.

Fishes have an array of discrete mechanical sensors at their disposal called neuromasts [4], which are distributed along with the head and trunk and form the fish's lateral line, as shown in Fig.1(a). With these neuromasts, local fluid motion and flow relative to the body can be perceived [5]. The neuromast is composed of a cluster of sensory hair cells, a cupula, support cells, and nerve fibers. Each hair cell carries a kinocilium and a bundle of stereocilia at its apical surface, which is enclosed in a gelatinous cupula. The mechanical stimulus is perceived by hair cells and then transmitted by nerve fibers.

In order to mimic this biological flow sensing, we demonstrate an optical fiber artificial neuromast, as illustrated in Fig.1(b). The artificial neuromast consists of a hair cell, a support cell, and an optical nerve fiber. The hair cell contains the kinocilium and stereocilia. The kinocilium has a height of 3 cm. There are two higher stereocilia with a height of 2 cm, and three lower stereocilia with a height of 1 cm. Note that all of the hair cells have a diameter of 125 μm. The support cell is made up of an aluminum film (thickness: 35 μm, diameter: 4 mm), a ceramic ferrule (diameter: 2 mm, height: 8 mm), and a glass tube (inner diameter: 2.5 mm, outer diameter: 4 mm, height: 5 mm).

Here, the aluminum film and glass tube were sealed together by ultraviolet (UV) glue, then the glass tube with the reflective film was tightly assembled to a ceramic ferrule, in which an optical fiber pigtail was fixed centrally. Finally, a cluster of single-mode fibers was regarded as the kinocilium and the stereocilia attached to the aluminum film.

The fiber-end surface and the aluminum film formed a sealed Fabry–Perot interferometer (FPI). When the water flowed through the sensor from the side, kinocilium and stereocilia will deflect, causing the deformation of the aluminum film. Thus, the cavity length of FPI will be changed, which will further induce a change of dip wavelength in the reflection spectrum of optical fiber. The relationship between the dip wavelength shift ($\Delta\lambda$) and the velocity variation (Δv) can be expressed as:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{V} \tag{1}$$

in which λ is the dip wavelength, and V represents the flow velocity. Therefore, the flow velocity can be calculated by tracing the dip wavelength shift of the reflection spectrum. As for water disturbance detection, such mechanical stimuli will induce the power variation of the reflected light so that water disturbance can be detected by the optical intensity.

3. Experimental setup and Results

To investigate the performance of the proposed sensor, the artificial neuromast was firstly utilized to sense water flow at different velocities. Fig.2 demonstrates the experimental setup of the water flow monitoring system. The micro-injection pump was used to generate water flows at different speeds. The artificial neuromast was placed at the outlet of the water tube which connected to the pump. The reflected light from the artificial neuromast was directed to an optical wavelength interrogator and the reflection spectrum was monitored in real time during the flow process.

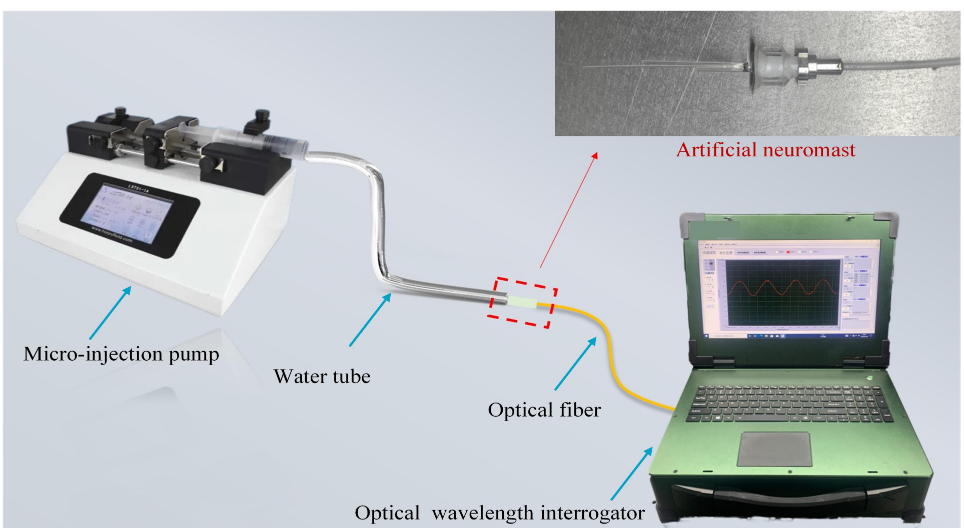

Fig. 2. The experimental setup of the water flow monitoring system. The inset shows the photograph of the artificial neuromast.

Fig.3(a) displays the dip wavelength shift process as the water velocity gradually increased from 0.01 to 0.05 mL/s in increments of 0.01 mL/s. It can be clearly observed that dip wavelength experiences a blue shift as velocity increases. The sensitivity is estimated from the slopes of the dip wavelength versus the flow velocity. As Fig.2(b) illustrated, the sensitivity is calculated to be 62.02 nm s/mL, and R-square (R^2), which describes how well the data matches the fit function, is 0.9978. Especially, the resolution of the wavelength interrogator is 0.02 nm, which corresponds to a velocity resolution of 0.32 μL/s. To compare the proposed sensor with the usual FP sensor without kinocilium and stereocilia, the sensitivity of the FP sensor which only consists of support cell and nerve fiber measurement was also measured. As the inset of Fig.3(b) demonstrated, a nearly 10-fold increase in flow velocity sensitivity was recorded, suggesting that kinocilium and stereocilia boost the sensitivity significantly. As listed in Table 1, the sensitivity of artificial neuromast is much higher than the other optical fiber sensors.

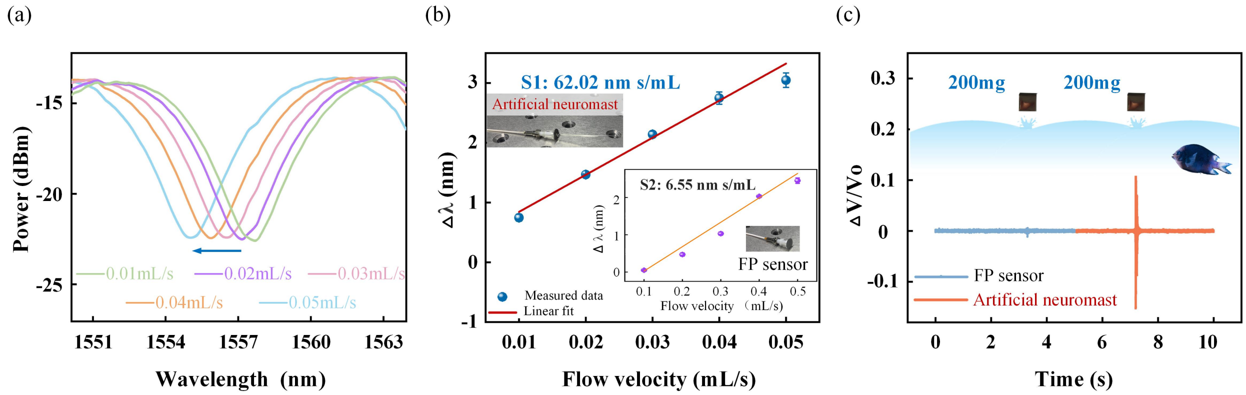

Fig. 3. (a) Evolution of reflection spectra of the artificial neuromast as the velocity increased. (b) The dip wavelength versus flow velocity and sensitivity comparison of artificial neuromast and usual FP sensor. (c) The detection comparison of water disturbance.

Table 1. Comparison of the fiber flow sensor

Configuration	Sensitivity nm s/mL	Range
FBG [2]	2.55	0-100 mL/s
Tunable polymer WGM laser [3]	0.00028	0-0.83 mL/s
F-P cavity [6]	0.03	0-8.3μL/s
Artificial neuromast [this work]	62.02	0-0.05 mL/s

Furthermore, water disturbance detection was also performed to verify the sensibilization of the artificial neuromast. A 200-milligram weight fell into the water where the artificial neuromast and usual FP sensor were immersed in. As Fig.3(b) exhibited, the FP sensor shows subtle fluctuations while the $\Delta V/V_0$ of artificial neuromast is higher than 0.1.

4. Conclusion

An optical fiber artificial neuromast inspired by fish lateral lines for versatile underwater safe navigation is proposed and experimentally demonstrated. The artificial neuromast consists of kinocilium, stereocilia, support cell, and optical fiber. The flow velocity is monitored in real time by the reflection spectrum. Linear velocity response is achieved with a high sensitivity of 62.02 nm s/mL (3.16 nm s/m) and a velocity resolution of 0.32 μL/s. The vibration of the water surface could be clearly detected. The reported results pave the way for new bionic instrumentation approaches in underwater perception with optical sensors that can be especially desirable in marine scientific exploration.

5. Acknowledgement

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6. References

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