

Recent Progress in Fiber-Optic Hydrophones

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Abstract: Fiber-optic hydrophone (FOH) is a significant type of acoustic sensor, which can be used in both military and civilian fields such as underwater target detection, oil and natural gas prospecting, and earthquake inspection. The recent progress of FOH is introduced from five aspects, including large-scale FOH array, very-low-frequency detection, fiber-optic vector hydrophone (FOVH), towed linear array, and deep-sea and long-haul transmission. The above five aspects indicate the future development trends in the FOH research field, and they also provide a guideline for the practical applications of FOH as well as its array.

Keywords: Fiber-optic hydrophone; large-scale array; very-low-frequency detection; fiber-optic vector hydrophone; towed linear array; deep sea; long-haul fiber transmission

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1. Introduction

Fiber-optic hydrophone (FOH) is a new generation of underwater acoustic sensor, which uses fiber as the medium of signal transmission and sensing. It has a variety of advantages such as high sensitivity, large dynamic range, small size, light weight, immunity to electromagnetic interference, and ease to large-scale arrays, so it has attracted wide attention since the first paper about FOH published in 1977 [1]. FOH is significant in both military and civilian fields, including underwater target detection, oil and natural gas prospecting, earthquake inspection. To date, FOH has a great many applications such as seabed fixed array, towed array, flank array, buoy, and subsurface buoy [2]. To be noticed, FOH has many different types which carry on modulation to optical parameters such as

intensity, frequency, wavelength, phase, and polarization. Among these types, the phase-modulated one, i.e., the interferometric FOH, has been especially widely used due to its highest sensitivity.

Owing to the huge potential for civilian and military applications, many countries have spent a great deal of efforts on the research and development of FOH since 1977 [3–30], e.g., Naval Research Laboratory (U.S.), QinetiQ (U.K.), and Optoplan (Norway). Although the start of FOH research is a little later in China [31], a series of key techniques have been broken through by some Chinese universities and research institutes since 1990s [32–52], and more attention has been paid to the practical applications of FOH array.

Recently, with the continual reduction of the underwater target radiation noise as well as the

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rising of ocean ambient noise (maritime shipping, seafloor mining, etc.), the detection difficulty of underwater acoustic signal using the FOH array is increasing rapidly. Also, the ocean oil-gas exploitation has extended from continental shelf to the deep sea and the request of stratigraphic structure resolution has become higher, which also puts forward new requirements to the FOH array.

To satisfy these requirements, many new techniques in the FOH field have been proposed and researched in detail. First, large-scale FOH arrays have been investigated to improve the detection performance of underwater acoustic signals. Second, considering that very-low-frequency noise ($<100\text{Hz}$) is the main noise source of underwater targets, the very-low-frequency detection is rather important for the military application of FOH. Third, fiber-optic vector hydrophone (FOVH) has also been widely researched because it can provide more complete information than the scalar one. Fourth, the towed linear array has drawn much attention due to its small diameter and flexibility to size-limited platforms. Finally, the FOH application is also moving towards the deep sea and long-haul transmission, so the pressure resistant performance and the fiber nonlinearity which were neglected before have become significant. In this paper, we review the recent progress in FOH from the

aforementioned five aspects.

2. Large-scale FOH array

For the traditional acoustic pressure FOH, it can be treated as scalar FOH without directivity, and the target direction is obtained by the beam-forming of the FOH array. The beamwidth as well as the direction precision depends on the array scale, so the large-scale array is used to improve the direction precision of the underwater target. Moreover, the large-scale array can improve the spatial signal-to-noise gain, which leads to an increase in the detection range. Therefore, expanding the array scale is significant for the performance improvement of the FOH array. There are many methods to expand the array scale such as space division multiplexing (SDM), wavelength division multiplexing (WDM), and time division multiplexing (TDM). To be noticed, compared with the large-scale optical communication system, the scale of the FOH array is usually smaller because FOH uses not digital signals but analog ones. On this condition, the array loss must be paid more attention. That is to say, with an increase in the array scale, the array will suffer larger loss resulting from more optical components. Therefore, it is a key technique to improve the overall performance of the FOH array by enlarging the array scale.



Fig. 1 Fiber-optic hydrophone array in USS Virginia [7].

Since more than twenty years ago, many organizations in the world have demonstrated various large-scale FOH arrays [53–66]. As the organization that invents the first FOH, United



States Naval Research Laboratory (NRL) has achieved great success in the application of the FOH array. In 1990, NRL conducted its first deployment of a 48-channel all optical towed array [67]. NRL

completed a few FOH array trials from 1990s to 2000s. In 2003, the first lightweight wide aperture array (LWAAA) consisting of 2 700 sensors went into service with the launch of USS Virginia, as shown in Fig. 1 [7, 68], which was a milestone in the development history of FOH. On the other hand, the large-scale FOH array gains much interest in the civilian field such as oil and gas exploration. In 2010, the Optoplan deployed a fiber ocean bottom seismic cable (OBC) system for the permanent reservoir monitoring at the Ekofisk filed in the North Sea, which consisted of 16 000 sensors in the wet end, as shown in Fig. 2. This project is the

largest fiber optic sensor network in the world to the best of our knowledge [69]. In 2013, a distributed amplified hybrid dense wavelength division multiplexing (DWDM) and TDM array architecture for the large-scale interferometric fiber-optic sensor array system was demonstrated, as shown in Fig. 3, which showed the potential for multiplexing and interrogating up to 4 096 sensors using a single fiber pair [63]. The array scale can be further enlarged by increasing the number of channels. In recent years, China has also developed the large-scale FOH array for scientific research and an FOH array with 1 024 sensors has been reported [66].

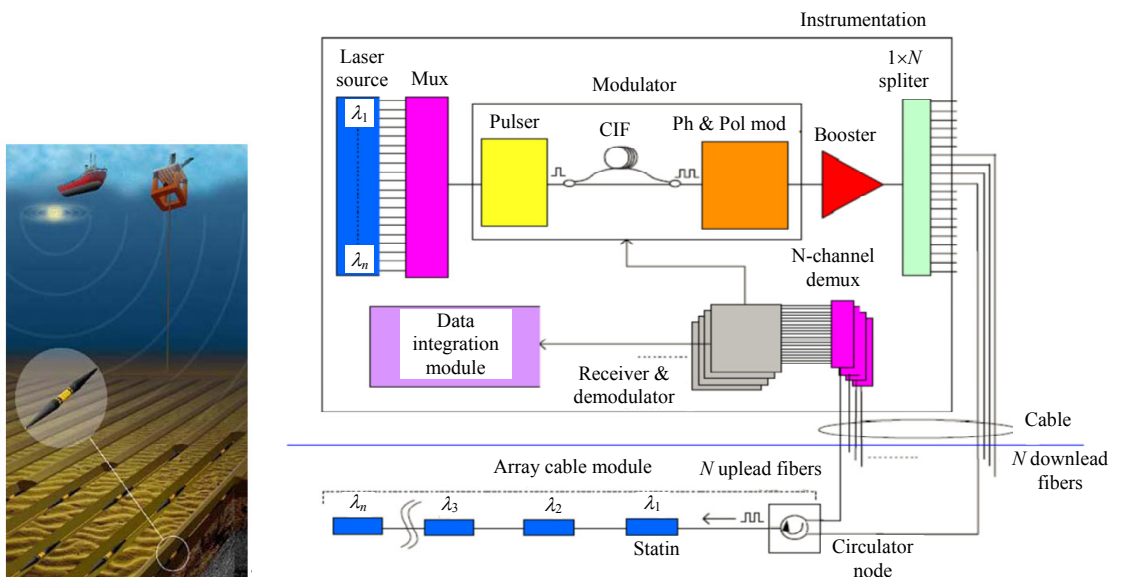


Fig. 2 Structure of the Optoplan array.

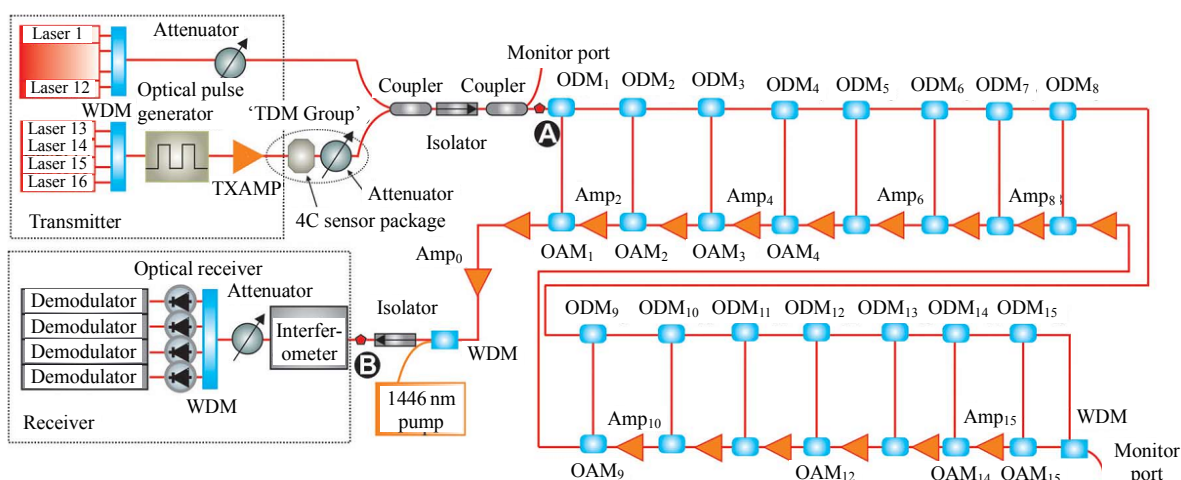


Fig. 3 Array architecture in [63].

3. Very-low-frequency detection of FOH

As mentioned above, the very-low-frequency noise (<100 Hz) accounts for the main part of underwater target noise. Compared with higher frequency, it is difficult to reduce the very-low-frequency characteristic signals of underwater targets. So the very-low-frequency noise is used to detect underwater targets. Also, the spatial and time coherence is strong for the very-low-frequency signals, leading to a high gain when a mass of sensors are used for long-time accumulation. It has also to be noticed that the very-low-frequency acoustic signals can propagate farther because of lower transmission loss. Therefore, it is promising to develop very-low-frequency FOH to realize the detection of underwater targets.

Due to the striking military background, the reports on the very-low-frequency detection are not sufficient. A relevant but not recent report was given by an Australian group that their fiber laser hydrophone possessed a flat acoustic responsivity of 110 dB re Hz/Pa from 40 Hz to 1 kHz, while a decrease was observed at the band lower than 40 Hz [70]. NRL demonstrated that the practical acoustic responsivity of their distributed feedback fiber laser (DFB FL) based scalar FOH was 107 dB re Hz/Pa over the bandwidth from 100 Hz to 5 kHz, which agreed well with the theoretically predicted value. However, as for the very-low-frequency band, they only provided the theoretical prediction between 30 Hz and 100 Hz due to the limitations of the underwater acoustic projector [71]. Recently, researchers in Russia have reported a hydrophone used in their towed array, but the acoustic pressure responsivity is not a flat pattern from 20 Hz to 495 Hz [72]. In contrast, a report from China has shown that the acoustic sensitivity is about 115 dB re Hz/Pa between 10 Hz and 10 kHz for their DFB FL-style FOH, which has improved the very-low-frequency detection ability compared with other designs [73]. The researchers from National University of Defense Technology (NUDT) have

also investigated very-low-frequency interferometric FOH with a sensitivity of -116 dB re rad/ μ Pa between 10 Hz and 2 kHz, phase noise of -102 dB re rad/Hz $^{1/2}$ @100 Hz, and equivalent noise pressure of 14 dB @100 Hz re μ Pa/Hz $^{1/2}$, as shown in Figs. 4–6. This equivalent noise pressure is far below the ocean ambient noise, making the very-low-frequency FOH a good choice for remote detection of underwater targets.



Fig. 4 Very-low-frequency interferometric FOH sensor head.

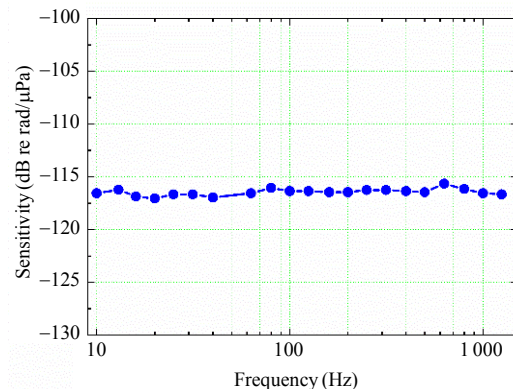


Fig. 5 Sensitivity of the very-low-frequency FOH.

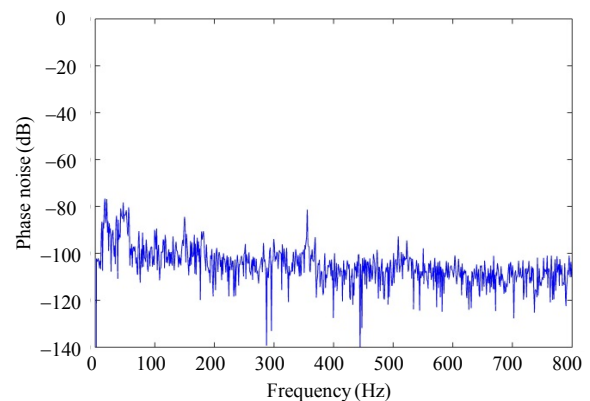


Fig. 6 Phase noise of the very-low-frequency FOH.

4. Fiber-optic vector hydrophone (FOVH)

Compared with the traditional scalar FOH, FOVH is generally composed of acoustic pressure hydrophone as well as three orthogonally mounted fiber accelerometers, which can obtain more complete acoustic information. For the FOVH, the cardioid directivity can be achieved with the linear combination of acoustic pressure and vibration velocity, and a spatial gain of 4.8 dB–6 dB is obtained accordingly. As a result, through only one point detection, the isotropic noise is suppressed and the port and starboard ambiguity is removed, which finally increases the detection range. Moreover, the directivity of the FOVH has no relation with the frequency, and the size of the FOVH array is smaller than that of the FOH array for the same technique specifications. Based on the above advantages, FOVH plays a key role in many military applications, especially in subsurface buoy and size-limited platforms.

The desired accelerometer that can be used in FOVH was firstly reported in the 1980's [74] and has experienced fast development in the past four decades [75–81]. On one hand, in terms of the structure, the general optical fiber accelerometer is a simple spring-mass system operating below the structural resonant frequency, but the concrete form is diverse. The compliant cylinder design appeared firstly [75] and has reached a mature level to date, which is generally adopted by researchers in Europe and Asia [80–87]. Most recently, a geophone for seismic monitoring, which consists of three orthogonal accelerometers based on the Michelson interferometers wound on the compliant cylinders, has been reported during the years from 2017 to 2020, which possesses an operation bandwidth of 2 Hz to 150 Hz, an acceleration responsivity of above 50 dB re rad/g, and a transverse suppression ratio of 30 dB [87]. The researchers from NUDT have investigated a FOVH with an acceleration sensitivity of 49 dB re rad/g, sensitivity fluctuation

of $\leq \pm 0.7$ dB, and an orthogonal crosstalk of ≤ -52.9 dB, as shown in Figs. 7–9, and the developed FOVH has a 66 MPa pressure resistant performance, which can be used in the 6 000 m deep sea. At the same time, in order to further explore the possibility for military applications, the institutes in US and Australia, represented by NRL, have turned their attention to the architecture based on a spring disk or beam since the beginning of 2000's, which possesses a more miniaturized, compact, and lightweight structure [88–90]. Relevant researches can only be traced back to the report in 2009, where a DFB FL is bonded to the surface of a flexural bend beam so that the operating wavelength can be modulated with the strain-induced flexion of the beam, achieving an acceleration responsivity of 142 dB re Hz/m·s⁻² from 10 Hz to 1.5 kHz, and a transverse suppression ratio exceeding 20 dB [89].



Fig. 7 Structure of FOVH.

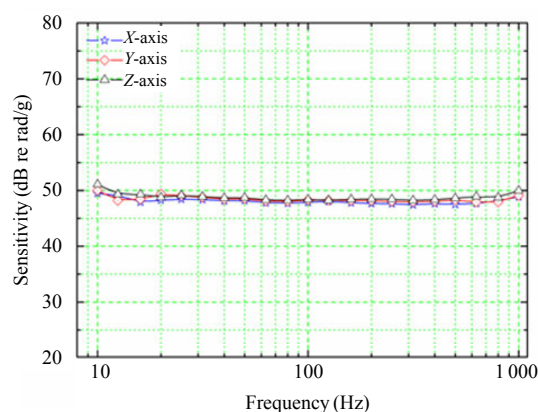


Fig. 8 Acceleration sensitivity of FOVH.

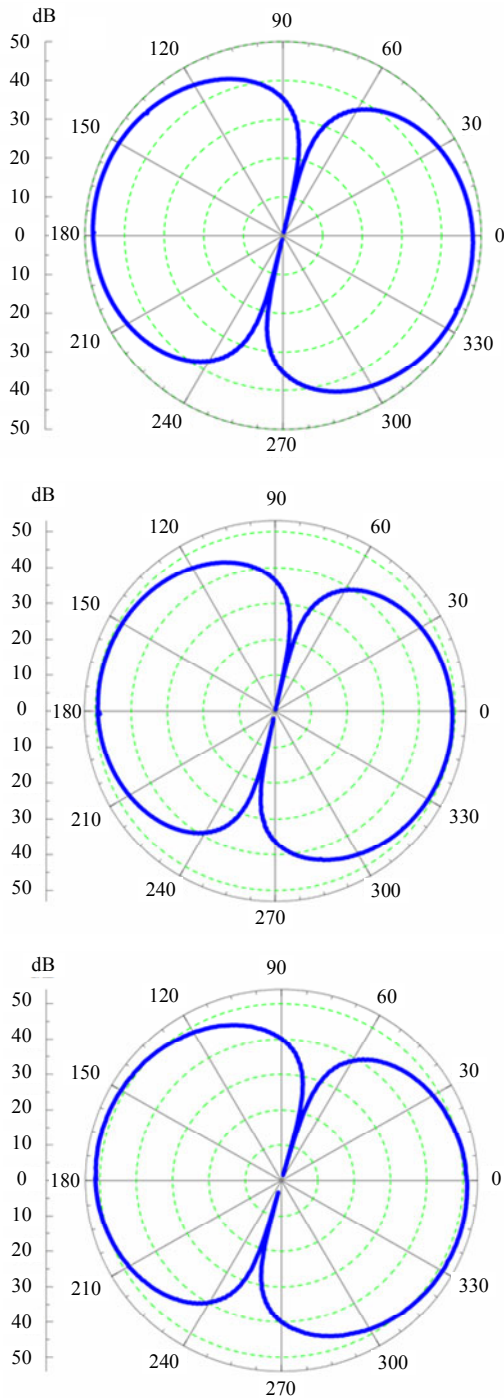


Fig. 9 Three-axis directivity of FOVH at the frequency of 160 Hz.

On the other hand, as for the sensing mechanism of the optical fiber accelerometer, the earliest and maturest scheme is based on the optical fiber interferometer, which is called the interferometric accelerometer [77, 80, 81, 85–87]. Nevertheless, the emphases have been put on the sensing schemes based on the fiber Bragg grating (FBG) or the DFB

FL by European [82–84] and USA researchers since middle 2000's, and the major concern is still the miniaturization of the design. Representatively, in terms of the FOVH, NRL has devoted most of the resources to the researches on the DFB FL-style one in the past 15 years, owing mainly to its striking advantages such as the small size and low noise [83]. The excellent achievement has also been reported in [79]. It should be pointed out that the DFB FL-style FOVH requires a fundamentally well-performed DFB FL with the intrinsic phase and intensity noise as low as possible. As a result, the researchers in NRL have never ceased exploiting the optimum performance of the DFB FL and have proposed complete theory in the recent report [91], which has marked the maturity of the DFB FL used for FOVH. In China, most recently, the typical FBG-type accelerometer has been reported to possess a flat acceleration sensitivity of 42 dB over the bandwidth from 20 Hz to 200 Hz [92], while the reported DFB FL-type one has the properties of a flat acceleration sensitivity of 33 dB re pm/g over the bandwidth from 5 Hz to 300 Hz [93].

Besides the accelerometer-type FOVH, NRL has also reported a velocity-style vector sensor on basis of a DFB FL bonded on a planar cantilever, which has pioneered in detecting the underwater acoustic particle velocity [94–96]. The ingenious design makes the sensor respond to the acoustic field with frequency independence and maintains the sensitivity over the operating bandwidth, overcoming the disadvantage of the accelerometer-type FOVH that the acoustic sensitivity diminishes with the decreasing frequency.

5. Towed linear array of FOH

Towed linear array is another typical application of the FOH and it is also suitable for the size-limited platforms. The main problem for towed linear array is the flow noise, which is difficult to remove. After many years of development, it is ensured that the flow noise remains almost the same level as the diameter of towed linear array decreases, leading to

the improvement of general performance.

The FOH was originally demonstrated by NRL to serve as the element of the towed linear array in 1970's, and the mature sign of the technology is the launch of the USS Virginia in 2003 which is equipped with a thinline towed array named as TB-33 [97]. Considering the suppression of the intrinsic noise and the prospective application on the mini underwater vehicles like the unmanned underwater vehicle (UUV), the development of the towed linear array has one trend towards designing a thinner towed cable. A report showed that an Australian-designed array had a practical diameter of only 25mm, which reached the advanced level at that time [98]. The reports from other countries have appeared successively in recent years. It was reported by an Indian group that their demonstration possesses an outer diameter of 32 mm [99]. The researchers from Russia reported an interferometric towed linear array with an outer diameter of 20mm, which is a real challenge for the interferometric scheme [72]. Almost simultaneously, Chinese researchers reported a sea trial using a 16-element DFB-FL based towed linear array with a diameter of only 12mm, and the towed noise of the array was 69 dB re mPa/Hz^{1/2} @1 kHz [100]. The researchers from NUDT carried out a lake trial with the 32-element FOH towed linear array and obtained a towed noise of 75 dB re μ Pa/Hz^{1/2} @100Hz at the speed of 6 knots, as shown in Figs. 10 and 11. Furthermore, they proposed a dynamic depth estimation method using the towed linear array [101].



Fig. 10 FOH towed array.

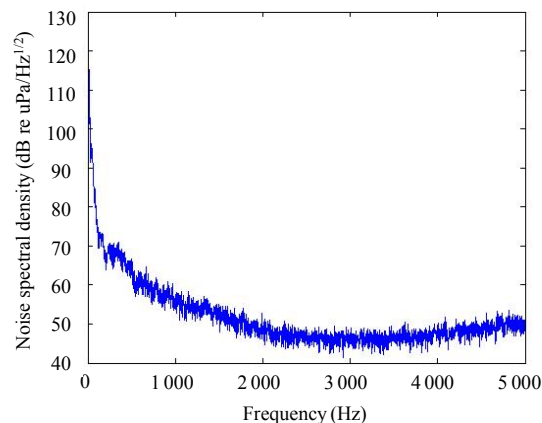


Fig. 11 Noise spectrum of towed array.

Another research focus lies in monitoring the gesture of the towed linear array. Recently, many researchers have put forward various methods to estimate the shape of the towed linear array and provided guidelines for the practical applications of the towed linear array [102–104].

6. Deep-sea and long-haul transmission

Owing to the advantage of detecting acoustic targets through deep-sea reliable acoustic path, the researches of the FOH move towards deep-sea application. The FOH and FOVH designed by NUDT have passed 66 MPa pressure resistant test, which have the potential for being used in the sea as deep as 6000 m. At the same time, with the developments of erbium-doped fiber amplifier (EDFA) and fiber Raman amplifier (FRA), the FOH system develops towards the direction of long-haul fiber transmission [52, 105–109]. There are two types of systems to realize long-haul fiber transmission, i.e., the repeater one and the repeaterless one. For the former, the transmission distance can reach almost 1 000 km, while it can reach 120km for the latter. To be noticed, the above distance is generally shorter than that of the long-haul fiber communication system, because the digital signals are used in fiber communication while the analog signals are used in fiber sensing. For the repeater system, the aforementioned Optoplan OBC system reached a 200 km transmission distance [69]. An FOH system with transmission distance as long as 500 km was also

reported [60]. In China, researchers from NUDT have developed an FOH array with the fiber transmission distance as long as 400 km using the cascaded-amplifier technique, as shown in Fig. 12, and the phase noise is about -90 dB re $\text{rad}/\text{Hz}^{1/2}@1$ kHz after the long-haul

transmission [110]. On the other hand, for the repeaterless system, with the longer transmission distance, various nonlinear effects become dominant, which leads to large power depletion and serious phase noise. As a result, the performance of the FOH array is degraded seriously [111].

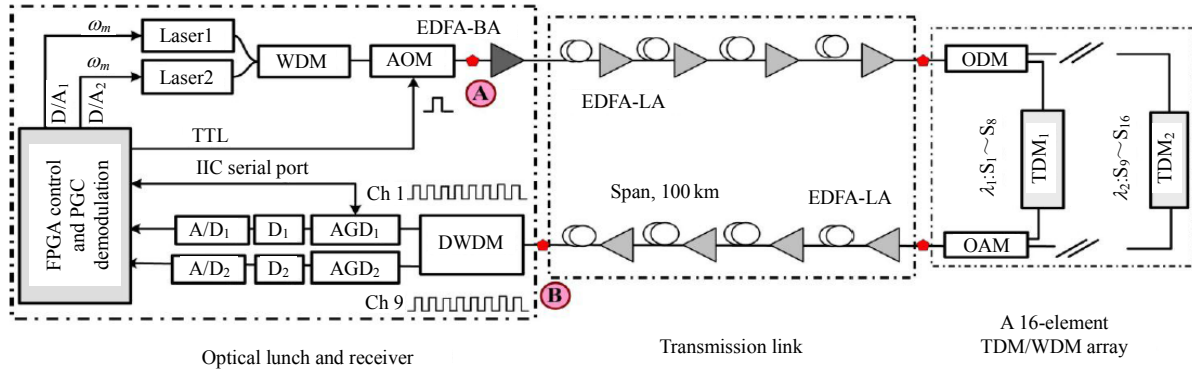


Fig. 12 400 km FOH system configuration in [110].

The maximum input power for fiber transmission is primarily limited by a nonlinear effect named as stimulated Brillouin scattering (SBS), which has the lowest threshold in the long fiber [112]. So the suppression of SBS in the long-haul FOH array is necessary. Many researchers studied the SBS suppression problem in various optical systems [113–119]. In the interferometric FOH system, the phase modulation method shows a great potential in SBS suppression for its convenience and high efficiency [120]. The effect of phase modulation on phase noise was studied in the interferometric fiber sensing systems, and the excess phase noise induced by phase modulation was observed in the experiment, which set a limit to the application of phase modulation [117]. A novel optical modulation method was proposed to suppress the phase modulation induced excess phase noise. However, theoretical analysis has not been derived to explain the excess phase noise in [117]. A detailed analysis was derived about the excess phase noise in the interferometric fiber sensing system, and a matching condition was proposed to suppress the excess phase noise [121], as shown in Figs. 13 and 14. As a result, SBS can be completely suppressed in the long-haul FOH system by increasing the number of the modulation sidebands.

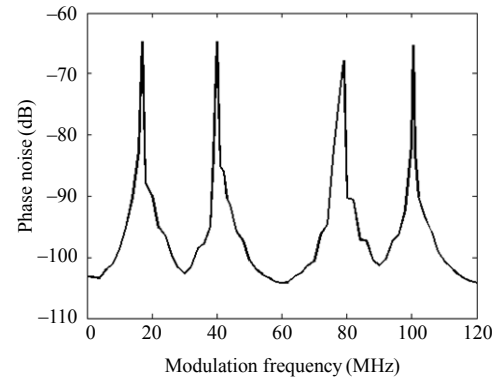


Fig. 13 Phase noise versus phase modulation frequency in [121].

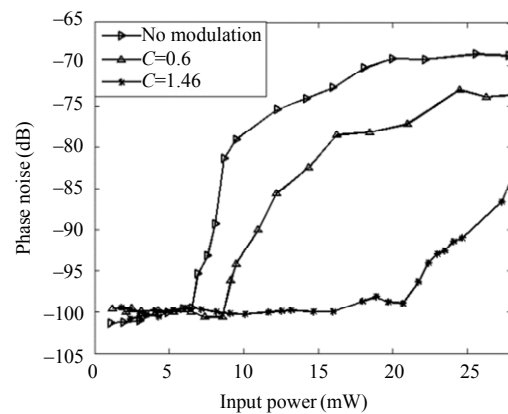


Fig. 14 Phase noise versus input power with different modulation indexes in [121].

Once the SBS is effectively suppressed, another nonlinear effect named as modulation instability (MI) becomes dominant especially in the TDM system

where optical pulses are used. The occurrence of MI generates symmetric sidebands by amplifying the amplified spontaneous emission (ASE) noise, which leads to serious phase noise [122]. Optical narrowband filtering is a direct solution to suppress MI, which is achieved by decreasing the ASE noise that seeds MI [123]. Orthogonal polarization pulses can increase MI threshold by 3 dB [124]. A method called time and frequency pump-probe multiplexing can increase MI threshold by N times (N is the number of spectral components), but the experimental setup is very complicated [125]. Spontaneous MI as well as the phase noise was suppressed with coherent seeds in the interferometric fiber sensing systems [126], as shown in Fig. 15, and the results showed that the average phase noise can be as low as about -90 dB re $\text{rad}/\text{Hz}^{1/2}$ @1 kHz when the input power is 800 mW, as shown in Fig. 16.

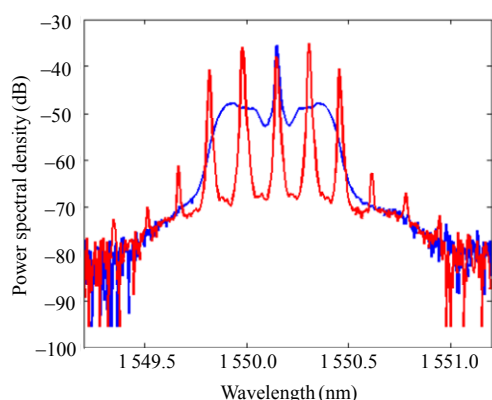


Fig. 15 Output spectra with an input power of 400 mW (blue: without seed; red: with seed).

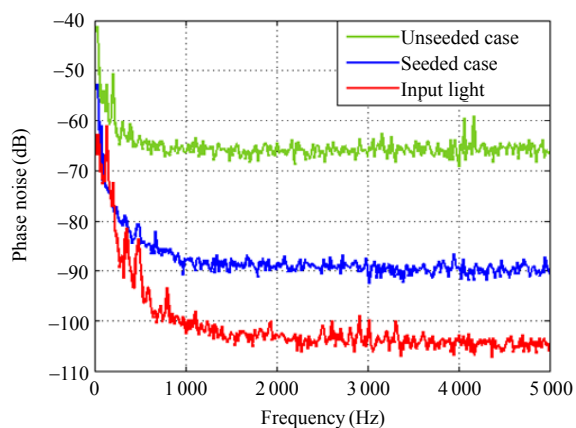


Fig. 16 Output phase noise without and with seed and the phase noise of the input light ($P=800$ mW).

7. Conclusions

In summary, to make the research progress of FOH clear, five aspects are reviewed in detail, including large-scale FOH array, very-low-frequency detection, fiber-optic vector hydrophone (FOVH), towed linear array, and deep-sea and long-haul transmission. The mentioned techniques will be very helpful for the research and practical applications in the FOH field. Furthermore, a great deal of advanced technologies based on new materials, new mechanisms, and new structures are expected to be used in the FOH to improve its characteristics and enlarge its applications in the near future.

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