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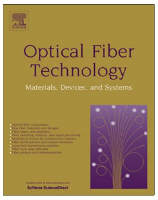

Regular Articles

Experimental investigation of the thin fiber-optic hydrophone array based on fiber Bragg gratings

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ABSTRACT

The paper presents the results of experimental investigations of the fiber optic hydrophone array consisting of six sensors, placed in one thin sensitive cable. Sensors were formed by pairs of Bragg gratings spaced 1.5 m apart and recorded in a birefringent optical fiber with the elliptical stressed coating. To form an extended sensor array the optical fiber was additionally covered with a silicone material RTV655 and protective coatings. Experimental investigations of the array showed that fiber-optic sensors pressure sensitivity increases as the acoustic frequency decreases at average value from −169.4 dB re rad/uPa at 495 Hz to −143.7 dB re rad/uPa at 40 Hz. The minimum detectable pressure was at average value from 53 mPa/$\sqrt{}$Hz at 495 Hz to 8.3 mPa/$\sqrt{}$Hz at 40 Hz. The obtained results might be used for developing and producing long thin hydroacoustic arrays for geophysical investigations and other hydroacoustic applications.

1. Introduction

Nowadays fiber optic hydroacoustic sensor systems are being actively developed for the needs of marine seismic exploration, civil and military hydroacoustic monitoring systems [1–3].

The main advantages of such fiber-optic systems over traditional hydroacoustic sensors based on piezoelectric transducers are easy multiplexing, reduced weight and size parameters, low cost, high reliability, ease of manufacturing of distributed sensors, high sensitivity and the immunity to electromagnetic interference [3,4].

Modern implementation techniques of fiber-optic sensors allow creating complex distributed hydroacoustic measurement systems. Using a birefringent optical fiber to avoid polarization fading problems in interferometric fiber-optic sensors [3,4], using of special coatings for optical fibers to increase their acoustic sensitivity [5,6] and using of Bragg gratings as low reflecting mirrors in optical fibers allows placing a large number of multiplexed sensors at a single optical fiber and producing long hydroacoustic arrays [7–10].

At present these systems are actively being developed and introduced in various fields of applications, such as for geophysical seismic exploration [11–13], perimeter security intrusion detection systems for ports and harbors [14] and a number of special applications [15,16].

But in spite of great achievements in the fiber-optic hydrophone technology, its implementation still involves considerable difficulties. These difficulties are connected with high requirements of the modern fiber-optic hydrophones, their production complexity, as well as characteristics repeatability.

The main purpose of this paper is to demonstrate the possibility of creating a thin fiber optic hydrophone distributed array, where each single sensor is formed by the birefringent optical fiber with an additional coating, increasing its hydroacoustic sensitivity. This approach to the implementation of the hydroacoustic sensors allows placing them inside a thin hydroacoustic cable in the longitudinal direction and leads to the cable diameter significant reducing at the same time.

2. Theory and simulation

2.1. Acoustic sensitivity of the optical fiber

The operating principle of the presented fiber-optic hydroacoustic sensor array is based on the acoustic pressure sensitivity of the optical fiber. This effect leads to a phase change of the light propagated along the fiber due to the fiber compression – extension processes caused by acoustic pressure changes.

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Calculation of the phase change in bare optical fiber in response to the acoustic pressure change might be executed using known expression [17]:

$$\frac{\Delta\varphi}{PL} = -\frac{\beta(1-2\mu)}{E} + \frac{\beta n^2}{2E}(1-2\mu)(2p_{12}+p_{11}) - \frac{V^3(1-2\mu)}{2\beta ED^2}\frac{db}{dV} \tag{1}$$

where $\Delta\varphi$ – the phase change, P – the acoustic pressure, L – the optical fiber length, Β – the propagation constant, n – the refractive index, μ – Poisson's ratio, E – Young's modulus, D – the diameter of the optical fiber, V – normalized frequency, p_{11} и p_{12} – elastooptical coefficients.

In the expression (1) temperature effects are not taken into account, since they make a little contribution into the phase change, compared with the deforming forces. According to the Eq. (1), the calculated phase change value for the uncoated silica fiber is $4.09*10^{-5}$ rad/(Pa*m) (−207.76 dB re rad/(uPa*m)) [17].

A well-known method for increasing acoustic sensitivity of optical fibers is their coating with the polymer layer, which Young's modulus less than one of the optical fiber. That leads to a significant increase in the axial load and, consequently, increases the phase change due to the acoustic pressure [18].

To increase sensitivity of the presented fiber-optic hydroacoustic sensor array a silicone material RTV655 with Poisson's ratio 0.49932 and Young's modulus 5.6 MPa might be used. Sensitivity of the optical fiber with the proposed additional coating could be calculated using known expression [19]:

$$\left(\frac{\Delta\phi}{P}\right) = k_0 nL\left\{\left[1-\frac{n^2}{2}(p_{12}-p_{11}\sigma-p_{12}\sigma)\right]\left[\frac{R^2(1-2\sigma\prime)+2r^2(\sigma'-\sigma)}{E'(R^2-r^2)+Er^2}\right] - \frac{n^2}{2}(p_{11}+p_{12})\frac{1-\sigma-2\sigma^2}{E}\right\} \tag{2}$$

where E и E′ – Young's modulus of the optical fiber and coating, σ и σ' – Poisson's ratio of the optical fiber and coating; p_{11} и p_{12} – elastooptical coefficients of the optical fiber. Since the Michelson interferometer is used in the presented array scheme (Fig. 3) and the light beam propagates twice through the each sensing element (optical fiber between two fiber Bragg gratings) – forward and backward after being reflected from the second Bragg grating, sensor's sensitivity, calculated according to the expression (2), should be doubled.

The dependence of the phase sensitivity Δφ/P on the coating radius (RTV655), calculated with expression (2) for the silica optical fiber with length L = 1.5 m and central wavelength λ = 1.55 um, is shown in Fig. 1.

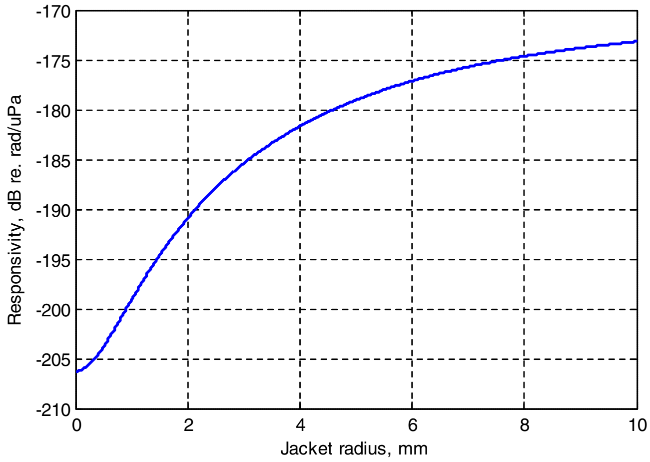

Fig. 1. The dependence of the phase sensitivity Δφ/P on the coating radius.

The fiber-optic sensor length of 1.5 m was performed to meet the requirement that sensor length should be equal or less than a half of the acoustic emission wavelength in water at 500 Hz.

2.2. Interferometric signals demodulation circuit

A homodyne demodulation technique based on the arctangent approach is used for interferometric signals processing [20–22]. The simplified scheme of this technique is shown in Fig. 2.where: FD – photodetector, ADC – analog-to-digital converter, RO – reference oscillator, LPF – low-pass filter, X/Y – division, atan – calculation of the arctangent function, Phase unwrap – fringe counter, HPF – high-pass filter.

In this scheme, the intensity of the interference signal at the photodetector is given by:

$$I_{in}(t) = A + B\cos[\cos(2\pi f_0 t) + \phi(t)] \tag{3}$$

where *A* and *B* are the values, determined by the intensity of the optical interference signal, and the visibility of the interference pattern at the photodetector, C – the phase modulation depth (rad), f_0 – the phase modulation frequency, $\varphi(t)$ – the measured phase signal. This signal according to the demodulation algorithm is multiplied by the reference oscillator signals and passes through low-pass filters that form a pair of quadrature signals (see Fig. 2). Further, these signals pass through the division block and then the arctangent function is calculated as:

$$S_{\text{out}}(t) = \arctan\left[\frac{J_1(C)}{J_2(C)}\tan(\phi(t))\right] \tag{4}$$

As it can be seen from Eq. (4), the output signal of the demodulation scheme is independent of the interference contrast *B* but depends on the measured phase signal and the phase modulation depth *C*. The optimum value of the phase modulation depth required for the correct operation of the described algorithm is equal to 2.63 rad. [11].

To provide correct operation of the demodulation algorithm at low frequency range (below 500 Hz) following implementation parameters of the considered demodulation scheme were selected: the ADC sample rate – 500 kHz; the carrier frequency – 31.25 kHz; the phase modulation depth *C* – 2.63 rad; low pass filter (LPF) passbands – up to 5 kHz; the upper limit of the dynamic range corresponding to the selected LPF bandwidth [23] – 10 rad (above 100 dB relative to the level of 100 urad); the high pass filter passband – from 5 Hz; the sampling frequency of the output signal – 5 kHz.

3. Experimental setup

The optical scheme of the investigated fiber-optic hydroacoustic sensor array is presented in Fig. 3. It consists of the optoelectronic generation and optical signals receiver unit («signal processing unit» in Fig. 3), the remote array of passive fiber optic

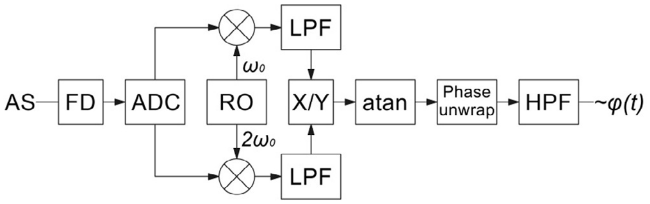

Fig. 2. Homodyne demodulation scheme based on the arctangent approach.