APPLICATION OF MICROWAVE PHOTONICS METHODS IN THE DESIGN OF MICROWAVE RECEIVING DEVICES FOR THE FORMATION AND REGISTRATION OF RADIO HOLOGRAMS

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Abstract. A scheme for implementing a microwave photonics receiving device for microwave signals for the formation and registration of radio holograms is proposed. The operation of such a receiving device was studied numerically and experimentally. A data processing method is proposed to reduce the error in determining the source coordinates.

Keywords: *microwave photonics, radio-photonic receiving channel, optical heterodyning*

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INTRODUCTION

Recently, the technology of radio vision in radiophotonic radars, which requires creating a radio portrait of "brilliant points" of a distant object in the microwave range, has become more and more in demand [1-4]. Such radars can be used for situations when the surrounding space requires precise control - in airports, seaports, in densely populated cities, on large highways, etc. The realization of this technology requires the creation of receiving radars for the "shining points" of a remote object in the microwave range. For realization of this technology it is necessary to create receiving devices with high resolution. In this case, the use of microwave receiving devices built on an exclusively radio-electronic component base may not always be suitable for solving this problem due to limitations on the operating frequency band. At the same time, higher range resolution can be achieved by using broadband and ultra-wideband pulses as localization signals [5-7]. High resolution in the angle of signal arrival at the receiving antenna can be obtained by using the holographic method, where to form a radio hologram to the reflected wave is added to the reference microwave wave and recorded the result of interference of the two waves, i.e., an electronic radio hologram is recorded, which can then be digitized and subjected to spectral analysis to extract information about the location of a distant object [8,9]. Receiving devices designed on the basis of radiophotonic technologies allow to realize the algorithm of formation and registration of radio holograms [10-12].

RECEIVER CIRCUIT

The scheme of the receiving device for the formation and registration of radio hologram is presented in Fig. 1. It is designed to solve the one-dimensional problem of determining the angle of arrival of the reflected signal to the receiving antenna from a distant object. The solution of this problem requires the formation and registration of the radio hologram of the reflected microwave wave from the object. For this purpose, the reference wave in the radiophotonic processing unit consisting of a fiber laser, a double parallel electro-optical modulator and a photodetector was mixed with the input signal of each receiver of the linear antenna array. As a result, an interference pattern of interaction between the reflected and reference waves was formed, i.e., the phase information of the reflected wave front was taken into account. Then the obtained interference pattern was subjected to spectral analysis, during which the angle of arrival of the reflected wave at the receiving antenna was determined.

STUDY OF CIRCUIT OPERATION BY MEANS OF NUMERICAL MODELING

Using numerical simulations in MatLab environment, the operation of such a system was investigated. The wave reflected from the object was considered as radiation with sinusoidal time dependence with a flat front (far zone). In such a case, the phase difference between the microwave signals recorded by neighboring receivers is constant. After mixing the reflected and reference signals in the double parallel Mach-Zehnder modulator and their subsequent photodetection, a signal is formed containing information about the intensity of the interference pattern of the reflected and reference wavesI_{p-r} at the location of the individual receiver. In this case, all optical frequency components are filtered. Provided that the phase difference of signals between neighboring receivers is constant,I_{p-r} is a sinusoidal function whose argument is the number of the receiver in the grating or its coordinates along the grating. That is, a spatial wave with a frequency that depends on the angle of incidence of the reflected wave on the array is formed on the array (the angle of incidence is counted from the vertical to the linear antenna array). Therefore, the angle of incidence can be determined by calculating the Fourier transform and finding the frequency maximum of the interference patternI_{p-r} .

The following circuit parameters were used in numerical simulations: UHF wavelength 3 cm, array length 1.5 m, number of receivers 100, distance between neighboring receivers of the linear antenna array 1.5 cm. The phase of the reference wave corresponded to the case of normal incidence (angle 0 degrees from vertical to the linear antenna array) when the reflected and reference signals were mixed in the Mach-Zehnder modulator. Fig. $2a$ demonstratesI_{p-r} as a result of time averaging for the case of a single reflecting object (noise was assumed small), Fig. 2b shows its spectrum. In the considered case, the reflected wave was incident on the antenna array at an angle of 50 degrees from the normal. The difference of the shapeI_{p-r} from the sinusoidal function is due to the relatively small frequency of the receivers' location on the spatial wavelength. However, the distance between the receivers on the period of the spatial wave is chosen to ensure that when the sliding incidence of the reflected wave on the period there are at least two digitization points to preserve the information.

In the case of low noise, the angle of incidence of the wave is determined with sufficient accuracy and is 50 degrees. In the case of increased noise, the accuracy of angle determination will be determined by the half-width of the spectral peak, i.e., the linear size of the antenna array. If we consider the half-width of the spectral peak at half power level, it is of the order of one degree, which corresponds to the diffraction width of the beam.

Fig. 2c showsI_{p-r} in the case of two reflecting objects located at angles of 25 and 50 degrees from the normal. Fig. 2g shows its spectrum. The directions to the two objects are well defined despite the more complex appearance ofI_{p-r} , due to the beat of two close frequencies of the reflected signals. Fig. 2d demonstrates the spectrum ofI_{p-r} for the case of two near-angle objects (the objects are located at angles of 20 and 21 degrees from normal). The objects can be resolved, which confirms the estimate made above.

EXPERIMENTAL STUDY OF THE CIRCUIT

A horn antenna is used as a source of the reflected wave in the scheme of the experimental model of the receiver for determining the angle of incidence of the signal (Fig. 1). The radiation from the microwave generator tuned to the frequency of 7.5 GHz is divided into 2 channels. The first channel leads to the horn antenna radiating the signal, the second - through an attenuator (20dB attenuation) to one of the arms of the double parallel Mach-Zehnder modulator, pre-tuned to the quadrature operating point (the middle of the linear part of the transfer function). The receiving antenna in the form of a section of rectangular waveguide, moved along the line 3, detects incident waves with a spherical front, radiated by the horn antenna. The signal from the receiving antenna is fed to a low-noise microwave amplifier (26 dB). The amplified wave is then fed to the second arm of a double parallel electro-optic modulator. Optical fields promoted by microwave signals received on both arms of the modulator are summed up and delivered to the photodetector via optical fiber. The microwave field obtained as a result of photodetection is fed to the power meter through the amplifier (23 dB). The measured power data are digitized and then analyzed using a software package in MatLab environment.

The circuit utilizes the following components:

- Agilent N1912A is a microwave power meter.
- The IXblue MXIQ-LN-30 is a dual parallel Mach-Zehnder modulator with 30 GHz bandwidth.
- Pure Photonics PPCL550 is a low-noise continuous single-mode laser with an emission wavelength of 1.5 μm.
- NPF Dilaz DFDShM40 is a broadband InGaAs PIN photodetector.
- Agilent 3 dB and 10 dB attenuators.
- Low noise amplifier with a bandwidth of 1 -- 18 GHz.

The experimental data obtained on the layout, the results of their processing, as well as their comparison with the theoretical model are presented in Fig. 3. 3. The interference pattern obtained during the experiment for the signal arrival angle of 30.8° is shown in Fig. *3a* (red curve 1). Its shape is similar to the curve in Fig. *2a* obtained from the numerical modeling of the circuit. In Fig. *3a* also contains a curve showing the result of interference in the case of a spherical wave field (blue curve 2), when the reflected object is at an insufficient distance from the receiving antenna. The phase difference of the two curves was a free parameter and was chosen from the condition of the closest possible match between the curves. It can be concluded that the theory gives a good enough match with the experiment.

Fig. *3b* demonstrates the angular spectra obtained by Fourier analysis of the interference patterns. The angle estimate made from the middle of the experimental distribution (at the -3 dB level) is 30.8°. This value coincides with the true angle in the experiment and is close to the angle of 30.2° obtained from the middle of the theoretical spectrum. The accuracy of the angle calculation is determined by the width of the distribution obtained from the Fourier analysis. In the considered case, the width of the spectrum is significant and is about 20°. This is due to the fact that the distance to the signal source is not large enough, so the incident wave is spherical rather than plane. As a result, the spatial wave period varies nonlinearly along the line of travel of the receiving antenna (linear antenna array). For small noise levels (signal-to-noise ratio more than 10-12 dB) this method of estimating the angle of arrival of the signal may be acceptable, but for more noisy data the processing algorithm must be modified.

The way to determine the true coordinates of the source is to solve the maximum likelihood equations using the method of successive approximations. The first approximation can be obtained by dividing the interference pattern data set into two equal parts corresponding to the right and left halves of the antenna array. During radiation registration, each part of the array detects the source at a different angle. In the considered case, these angles are 26° and 36° according to spectra 1 and 2 in Fig. *3в*. The point of intersection of straight lines passing through the centers of the halves of the antenna array at the found angles gives information about the position of the source in the first approximation (Fig. *3d*). In the considered case of data processing, the measured value of the signal arrival angle is 31.4 degrees. Thus, the angle error is less than 1°, and the x and y coordinates of the true (265,342) and reconstructed (241,285) sources differ within 10% and 20%, respectively.

CONCLUSION

The problem of determining the angle of arrival of a reflected wave on a linear antenna array is considered. A scheme of a UHF radiophotonic receiving device for the formation and registration of radio holograms is proposed. Numerical and experimental studies of such a device are carried out. An algorithm of interference pattern processing for determining the coordinates of the reflecting object in the case of sphericity of the reflected wave at insufficient distance of the receiver from the object is proposed. The data array from the antenna array is divided into two parts to determine the angle of incidence on each of them. The point of intersection of the lines passing through the centers of the halves of the antenna array at the found angles can be used as a first approximation to the true coordinates of the reflecting object, which can be refined using the maximum likelihood method.

REFERENCES

1. *Dong J., Zhang F., Jiao Z., Li W.* // Optics Express. 2020. V. 28. No. 13. Art. No. 19113.
2. *Pan S., Ye X., Zhang Y. et al.* // IEEE J. Microwaves. 2021. V. 1. No. 1. P. 176.
3. *Dong J., Sun Q., Jiao Z. et al.* // Photonics Res. 2022. V. 10. No. 7. P. 1679.

4. *Pan S., Zhang Y.* // J. Light. Technol. 2020. V. 38. P. 5450.
5. *Kulagin V.V., Valuev V.V., Kontorov S.M. et al.* // Bull. Russ. Acad. Sci. Phys. 2021. V. 85. No. 1. P. 70.
6. *Kulagin V.V., Valuev V.V., Kontorov S.M. et al.* // Bull. Russ. Acad. Sci. Phys. 2021. V. 85. No. 1. P. 750.
7. *Kulagin V.V., Valuev V.V., Burkitbaev D. et al.* // Bull. Russ. Acad. Sci. Phys. 2023. V. 87. No. 1. P. 40.
8. *Fan B., Zhang F., Ma C. et al.* // IEEE Photonics Technol. Lett. 2020. V. 32. No. 21. P. 1397.
9. *Zhang F., Guo Q., Wang Z. et al.* // Opt. Express. 2017. V. 25. No. 14. Art. No. 16274.
10. *Wang A., Wo J., Luo X. et al.* // Optics Express. 2018. V. 26. No. 16. Art. No. 20708.
11. *Valuev V.V., Kulagin V.V., Ryzhuk. R.V. et al.* // 5th Int. Conf. TERA-2023. (Moscow, 2023). P. 125.
12. *Kulagin V.V., Valuev V.V., Kargin N.I. et al.* // In Proc. "Mokerovskie readings". M.: NIAU MIFI, 2023. 39 c.

FIGURE CAPTIONS

Fig. 1. Scheme of the receiving device: 1 - radiating antenna, 2 - receiving antenna, 3 - line of travel of the receiving antenna, Θ - angle , L - distance between the radiating and receiving antennas, OF - optical fiber, MZM - double parallel electro-optic Mach-Zehnder modulator, PD - photo detector, Analysis - analysis with the help of software package, Result - output data.

Fig. 2. Signal at the photodetector output for a single reflecting object located at an angle of 50 degrees from the normal: time-averaged intensity of the interference patternI_{p-r} (a); spectral viewI_{p-r} (b). Signal at the output of the photodetector in the case of two reflecting objects: time-averagedI_{p-r} for objects located at angles of 25 and 50 degrees from the normal (c) and its spectral view (d); spectral viewI_{p-r} (e) in the case of two closely located targets at angles of 20 and 21 degrees.

Fig. 3. Experimental data and results of their processing. Comparison of experimental and theoretical interference patterns (a) and angular spectra (b): 1 - experiment, 2 - theory (spherical wave). Proposed algorithm of experimental data processing (c): 1, 2 - spectra of data obtained from the right and left halves of the antenna array, 3 - full spectrum for comparison. Initial and reconstructed target coordinates (d): 1 - true position of the source, 2 - reconstructed position, yellow line - antenna array.

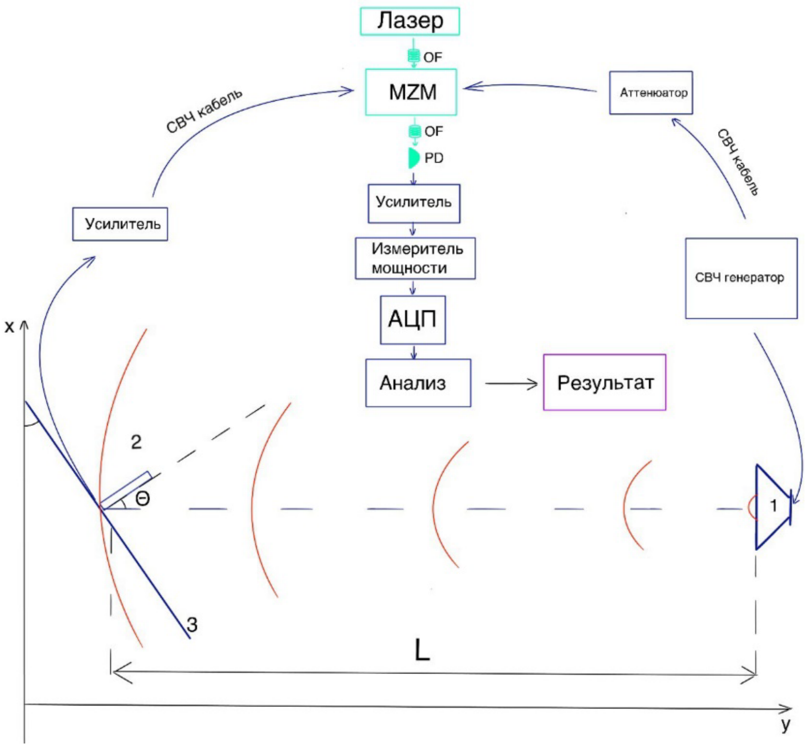

Fig. 1.

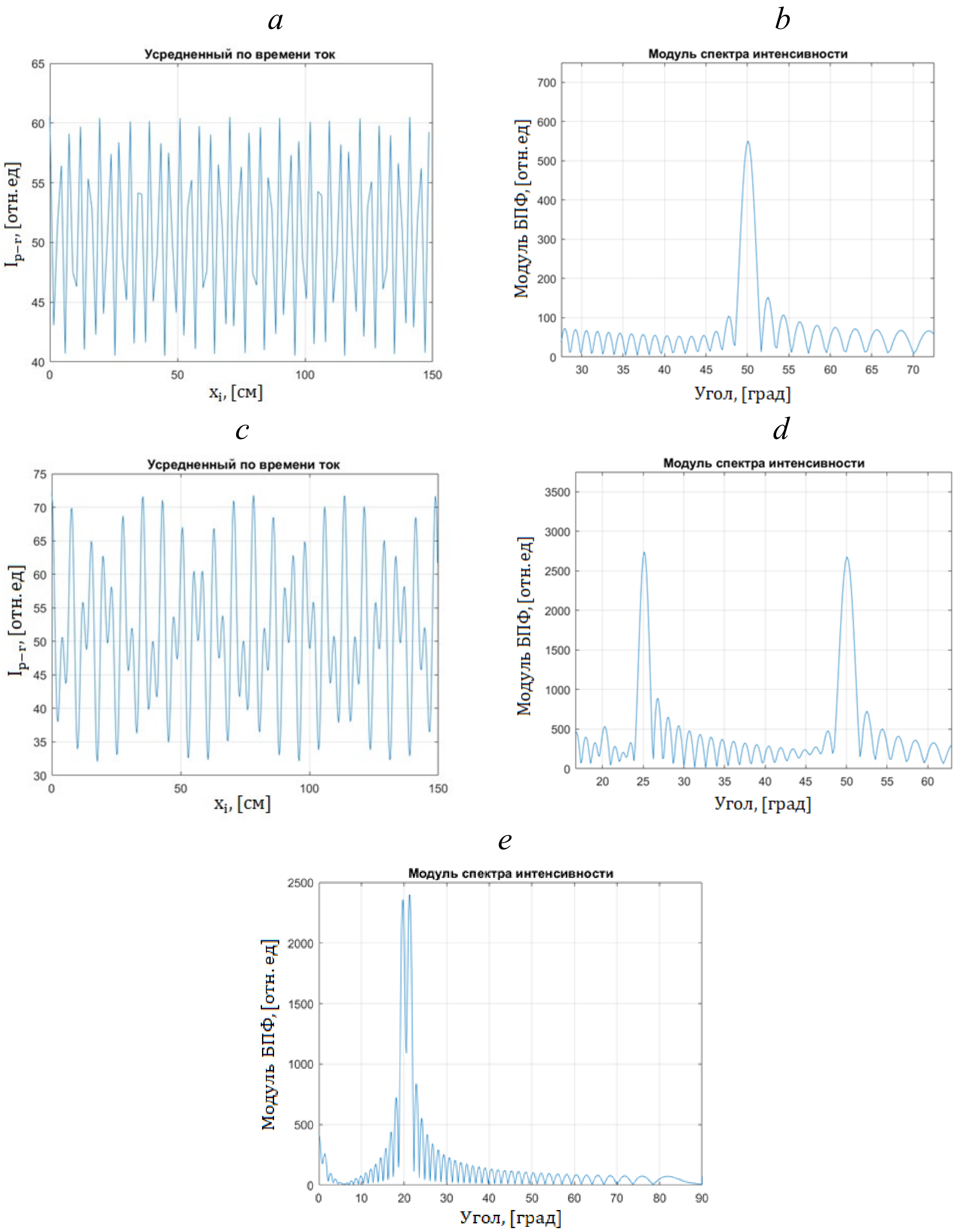
a
Усредненный по времени ток
I_{p−r}, [отн.ед]
x_i, [см]
b
Модуль спектра интенсивности
Модуль БПФ, [отн.ед]
Угол, [град]
c
Усредненный по времени ток
I_{p−r}, [отн.ед]
x_i, [см]
d
Модуль спектра интенсивности
Модуль БПФ, [отн.ед]
Угол, [град]
e
Модуль спектра интенсивности
Модуль БПФ, [отн.ед]
Угол, [град]

Fig. 2.

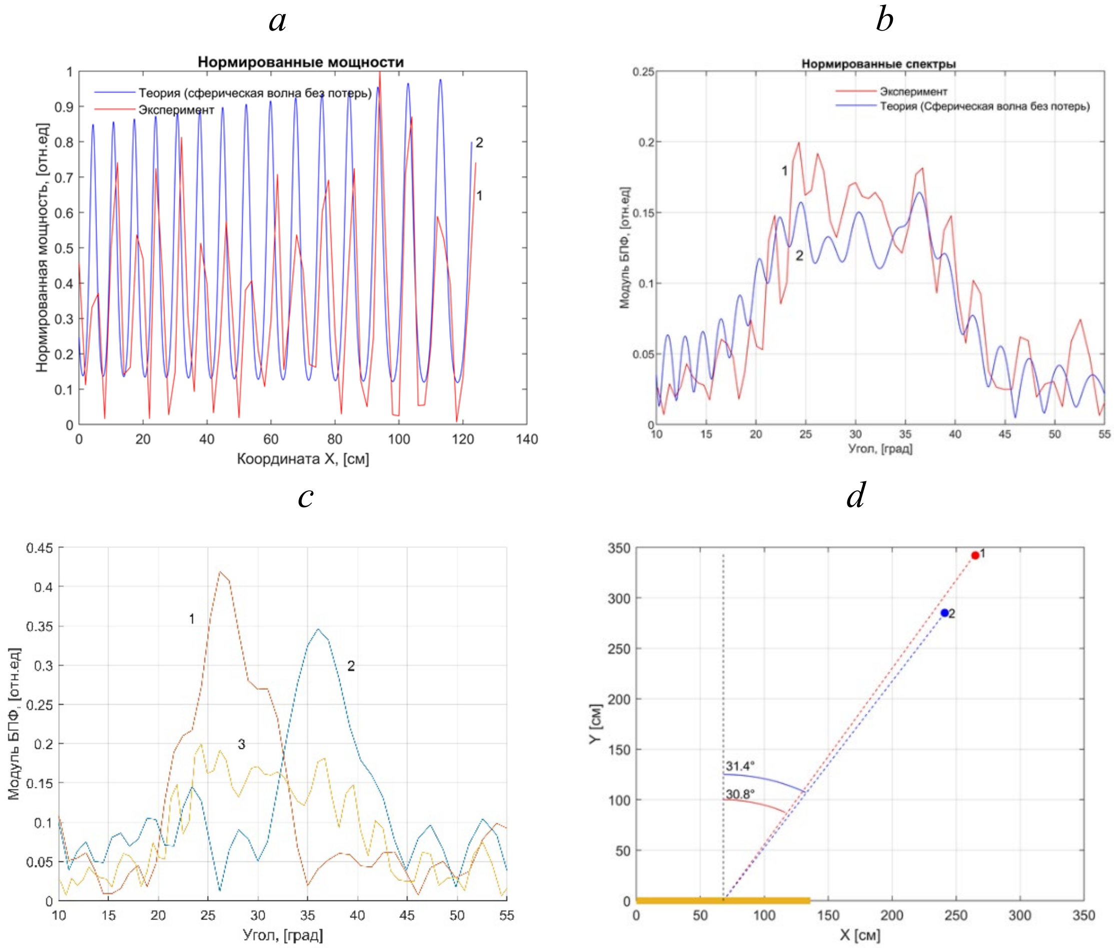
a
b
c
d
Нормированные мощности
Теория (сферическая волна без потерь)
Эксперимент
Нормированная мощность, [отн.ед]
Координата X, [см]
Нормированные спектры
Эксперимент
Теория (Сферическая волна без потерь)
Модуль БПФ, [отн.ед]
Угол, [град]
Модуль БПФ, [отн.ед]
Угол, [град]
31.4°
30.8°
Y [см]
X [см]

Fig. 3.