Paper

Radio Photonic Systems for Measurement of Instantaneous Radio Frequency with Amplitude-phase Modulation of Optical Carrier

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Abstract—In this article questions related to the development instantaneous radio frequency measurement system based on application in them original ways of the amplitude-phase modulation transformation of single-frequency optical carrier by a radio signal in symmetric two-frequency and measuring “frequency-amplitude” transformation in fiber Bragg grating with special profile are considered. Such systems have broad prospects for use in telecommunications, military systems and for environmental monitoring.

Keywords*—*amplitude-phase modulation, transformation, fiber Bragg grating, instantaneous frequency, radio photonics.

1. Introduction

With development of radio photonics the measurement systems of radio signals instantaneous frequency (MSRSIF) become one of perspective tools applied in various military and civil systems, designed on the principles of complex processing of radio signals in the optical range of electromagnetic waves.

In comparison with classical methods [1], which use radio-electronic multichannel technologies, radio photonic MSRSIF have essential advantages on the wide frequency and amplitude range of measurements, small losses, a high electromagnetic noise stability, and also simplicity, compactness and small weight [2]. Traditional electronic technologies of MSRSIF [1] estimating phase change rate, by selecting radio signal carrier (continuous or pulsed) with highest amplitude. The system receives signal measurements for a fixed period time in a multi frequency device, where multi-channel feature is designed by narrowband phase discriminator. Radio photonic MSRSIF technology [2] includes modulation transformation of optical carrier by radio signal. With the “time-frequency”, “frequency-space” or “amplitude-frequency” measurement conversion types, opto-electronic transformation in the photodetector and calculating temporal, spatial or amplitude ratio function is uniquely dependent on the measured signal frequency (compared to reference) to eliminate the influence of instabilities.

The modulation of intensity or phase in Mach-Zehnder Modulator (MZM), parallel modulation of the intensity and phase in the polarization modulator (PolM) are used for modulation transformation [3]–[5]. There is conducted research method on the using only amplitude modulation with suppressed optical carrier in MZM and PolM circuits, during their operation in the “zero” point of the modulation characteristic.

MSRSIF is seen as the most forward-coding technologies of determining the frequency with “amplitude-frequency” transformation type in optical mediums, including those in Fiber Bragg Grating (FBG) [6]–[8]. Benefits of using FBG are in a unique transformation of the measured frequency to the amplitude of the reflected or transmitted radiation of optical carrier, modulated by RF signal, and the possibility of a simple fabrication. The main disadvantages of the FBG are monotone measuring conversion to the central wavelength and the high level of gratings response on temperature and deformation. In typical implementation the amplitude and phase modulation the bandwidth defined sidebands are usually two or four times the measured frequency. This leads to the need for “wide-band” FBG, with a low reflectance and monotonic profile in the resonance region.

In recent years, a significant attention is paid to determining the spectral characteristics of the optical fiber selective structures based on the use as probing signal a symmetrical two-frequency or polyharmonic continuous wave with suppressed carrier. The signal is synthetized from the carrier using its sequential amplitude phase modulation transformation (AFMT) by the Ilyin-Morozov method. It is based on 100% amplitude modulation of a single frequency coherent radiation with sequential switching on the π phase, while the envelope of amplitude modulated radiation passing the minimum [9]–[12]. Its features include high spectral purity of the output radiation and the conversion factor, as well as the possibility of obtaining the difference frequency equal to the modulation frequency. The latter feature was never before used in applications of optoelectronic systems, and is the basis for this work.

The conducted analysis allowed to formulate the design requirements for the radio photonic MSRSIF, which are the need to use in its structure only one laser, a minimum of one modulator, one FBG and possibly only one narrowband photodetector [13]–[17]. General requirements for the monitoring channel of operating modes are determined by the need to use a symmetric dual-frequency radiation to control the position of the FBG central wavelength and control the amplitude modulators operating point [18], [19].

2. The Amplitude-phase Modulation Conversion of Optical Carrier

In this section authors briefly discuss features of AFMT and forming signal a symmetrical dual-frequency radiation with suppressed carrier by radio. In the analysis a classic generalized scheme of single-port radio photonic conversion unit for modulating the optical carrier is considered [20], which has been transformed from parallel to serial circuit type (Fig. 1) in order to implement the AFMT method of Ilyin-Morozov.

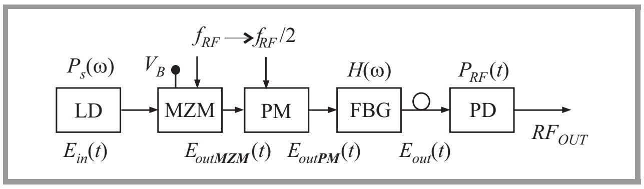

Fig. 1. A generalized block diagram of serial type single-port radio photonic unit of modulation conversion: LD – laser diode, MZM – Mach-Zehnder modulator, PM – phase modulator, FBG – fiber Bragg grating, PD – photodetector.

The investigations showed the possibility of AFMT implementing based on sequentially arranged amplitude and phase MZM. The obtained equations were used to calculate the spectrum of the radiation at the output of modulators. It was shown that the AFMT implementation to obtain the difference frequency equal to the measured frequency of the radio signal is possible. The optimal modulation factor $m = 5/9$ in the case of modulating type oscillations as $S_1(t) = S\cos(2\Omega t + \pi)$ and $m = 1$ in the case of oscillations of the form as $S_2(t) = S|\sin\Omega t|$, where $\Omega = f_{RF}/2$ and f_{RF} – radio frequency. The radiation spectrum for the two components of the modulator output in the case $S_1(t)$ is described by:

$$E_{APM}(t) = 0.49E_0\{\sin(\omega_0+\Omega)t - \sin(\omega_0-\Omega)t\} - \\ -0.007E_0\{\sin(\omega_0+3\Omega)t - \sin(\omega_0-3\Omega)t\} + \ldots, \quad (1)$$

and in case of the modulation by oscillation $S_2(t)$:

$$E_{APM}(t) = 0.56E_0\{\sin(\omega_0+\Omega) - \sin(\omega_0-\Omega)t\} + \\ +0.05E_0\{\sin(\omega_0+3\Omega)t - \sin(\omega_0-3\Omega)t\} + \ldots, \quad (2)$$

As can be seen from Eqs. (1) and (2) the difference frequency between the components of the two-frequency radiation 2Ω equal to modulating signal frequency f_{RF}. The higher harmonics can be ignored due to their low amplitudes. The narrowing of the difference frequency is twice more as compared with the classical scheme of its doubling applied in known radio photonic MSRSIF, using a single amplitude MZM working at zero point of the modulation characteristics to suppress the carrier.

3. Improving the Metrological Characteristics of the Radio Photonic MSRSIF

This section describes three methods of improving the characteristics of existing radio photonic MSRSIF: widening the range, increasing the measurements resolution at low frequencies and sensitivity at high measured frequencies.

Let us consider a short theoretical substantiation of MSRSIF method with the widening conversion measurements in twice frequency range. The block diagram for its implementation is shown in Fig. 2a, an explanation of the operating principle is shown in Fig. 2b, and the measuring characteristics is presented in Fig. 2c. The optical carrier from a laser diode LD at the frequency f_0 is supplied to the M2M and PM modulators block MB where is modulated by unknown frequency f_{RF} and amplitude A_{RF} microwave signal, and then divided into two channels in the optical splitter OS.

On first channel the radiation through the circulator C entrance is fed to FBG, and then reflected from it and from the output C is applied to the first photodetector PD1. The second channel with PD2 is used as a reference. The microcontroller MCU detects the microwave signal and computes the parameters according to the ratio of the signals amplitudes from PD1 and PD2 output using the amplitude comparison function, that uniquely depends on the frequency of the microwave signal and does not depends on the power of the laser radiation. According to the Eqs. (1) or (2) the output radiation from MB is a dual-frequency with $f_0 - f_{RF}/2$ and $f_0 + f_{RF}/2$ sidebands and suppressed carrier f_0. Amplitude of the components A_{-1} and A_{+1} are determined by the value of the Bessel function.

The output current of PD2 from the reference channel is proportional to

$$i(t) \propto A_{-1}^2 + A_{+1}^2 + A_{-1}A_{+1}\cos 2\pi f_{RF}t\,, \quad (3)$$

and DC detecting power at $A_{-1} = A_{+1} = A_1$:

$$P_{RF} \propto A_{-1}^2 + A_{+1}^2 = 2A_1^2\,. \quad (4)$$

For amplitude-frequency measurement conversion, a classical FBG with a Gaussian profile of the envelope with center frequency f_B is chosen, which is characterized by dependence

$$R(f_{RF}) = R_B\,\mathrm{e}^{-4\ln 2\left(\frac{f_{RF}-f_B}{\Delta f_B}\right)^2}, \quad (5)$$

where: R_B – reflectance at f_0, Δf_B – full width at half maximum of FBG.

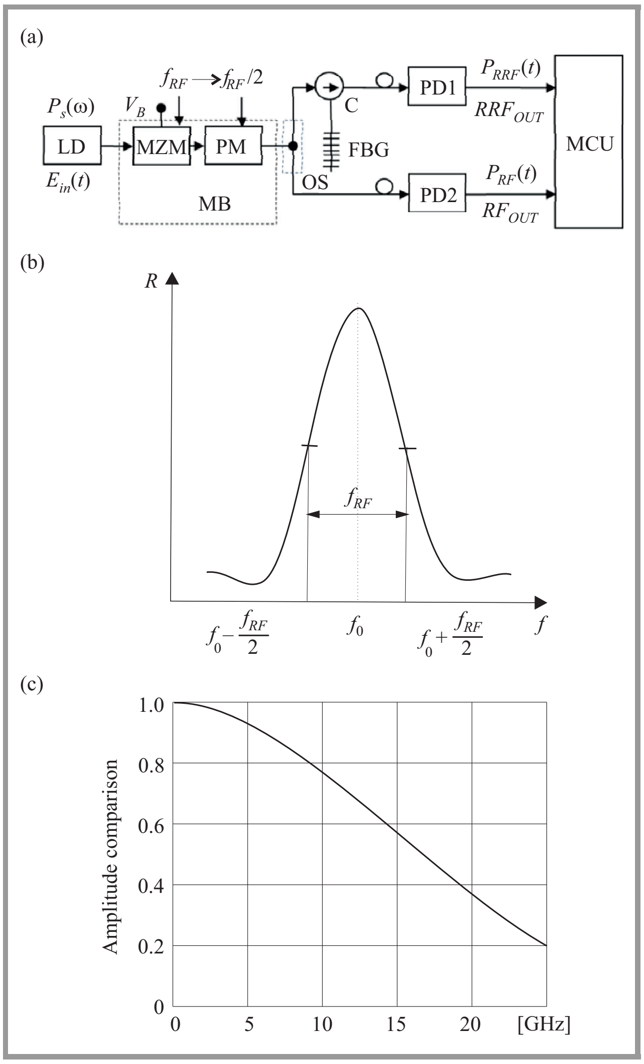

Fig. 2. To theoretical justification of the way of expand the range of measured frequencies: (a) block diagram, (b) spectral representation, (c) measuring characteristics.

Thus, when the FBG center frequency is tuned to the frequency of the optical carrier, the two-frequency components of radiation reflected from the FBG (depending on the frequency) have amplitude:

$$A^R_{-1}RF = A^R_{+1}RF = A_1 R(f_{RF}), \tag{6}$$

and the PD1 output power in the measuring channel:

$$P_{RRF} \propto= 2A_1^2 R^2(f_R F). \tag{7}$$

The frequency dependent function of the power ratio, defined as $\rho = P_{RRF}/P_{RF}$, equal to:

$$\rho = R^2(f_{RF}). \tag{8}$$

Figure 2c shows a unique dependence between ρ and f_{RF}, calculated in Matlab, which is independent of the laser power and the power of the microwave signal.

Thus, knowing only the power ratio ρ, the instantaneous frequency of microwave signal f_{RF} could be determined. The amplitude of the unknown microwave signal is determined by the output signal of PD2 at the calibrated power of DFB-laser and the known characteristics of the modulation conversion in the modulator block.

The difference frequency between the components of the two-frequency signal is equal to the measured frequency, allowing for the twice extension the range of measured frequencies in comparison with the classical methods of MSRSIF at a predetermined full width at half maximum of FBG.

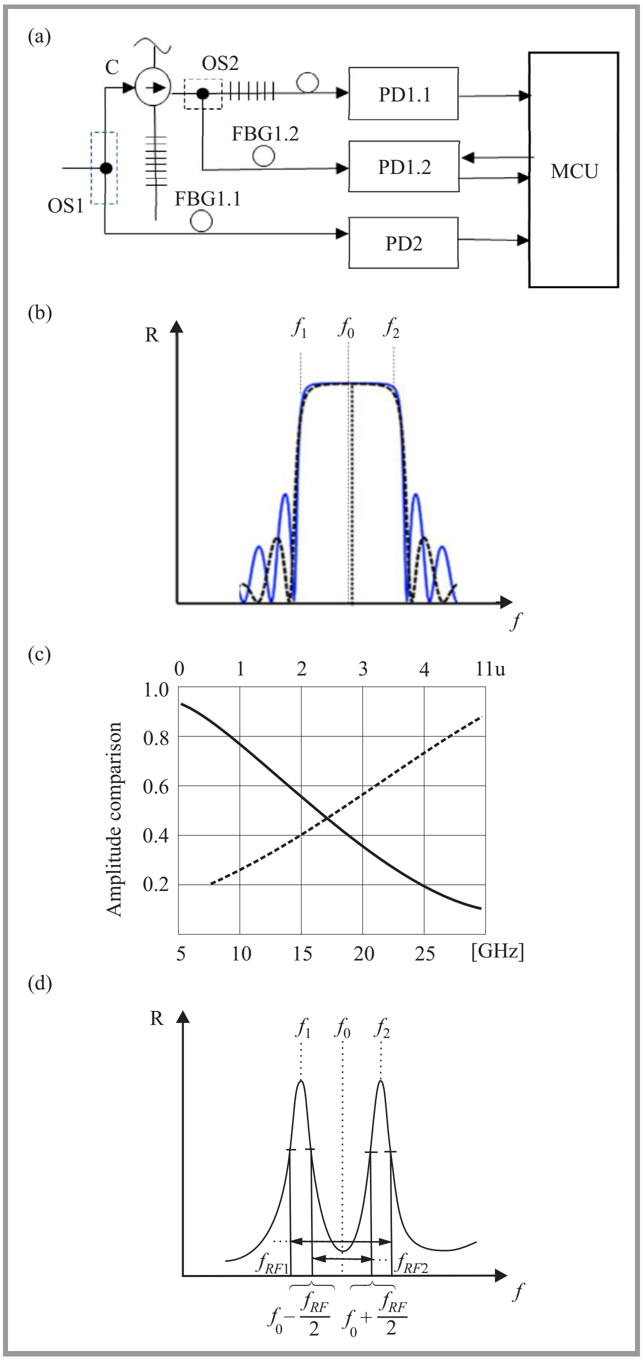

Fig. 3. MSRSIF test circuit for increasing the resolution of the measurements in the area of low measured frequencies: (a) block diagram, (b) spectral representation, (c) measuring characteristics, (d) contour of band stop FBG1.2.

In the next step let us consider a method to improve the measurements resolution on the low measured frequency. When using classical FBG in this area the monotonous envelope is observed (Fig. 2b), resulting in a reduction of measurement resolution. To improve FBG with π-phase shift and frequency response with a special form has been used, which has a transparency window in the low frequencies. It allows to create dual-band setup. The block diagram of the setup is shown in Fig. 3a, an explanation to the principle of the work is presented in Fig. 3b, and measuring characteristics is shown in Fig. 3c.

To separate signal ranges FBG1.2 was used with rectangular form (Fig. 3d) in the frequency range from f_1 to f_2 ($\pm$4 GHz) to provide lower and higher channels and a special switching algorithm in the MCU. Above 4 GHz PD1.1 and PD1.2 channel blocked by MCU. In frequencies up to 4 GHz the PD1.2 channel is activated by MCU, because the signal level in the channel with PD1.1 lies below a predetermined threshold.

The results of numerical simulations in Matlab, confirming the possibility of increasing the resolution in the low frequencies to the level of resolution in the medium and high frequencies of 0.8–1 GHz/dB are shown in Fig. 3c.

Based on the analysis of noise characteristics of radio photonic systems, implementing a variety of receiving variants of two-frequency radiation (in the band of the measured frequency and constant component) a technique of splitting components of two-frequency radiation at a fixed difference frequency $f_{DF} = 100$ MHz is proposed, which is in the region of photodetector minimal noise (Fig. 4a). This provided a narrow-band receiving and registration of the measured components amplitude according to the envelope of split components (Fig. 4b) on f_{DF} when filtering in units of frequency selection UFS (narrow-band filter with a center frequency of 100 MHz and a minimum bandwidth defined by the width of the laser).

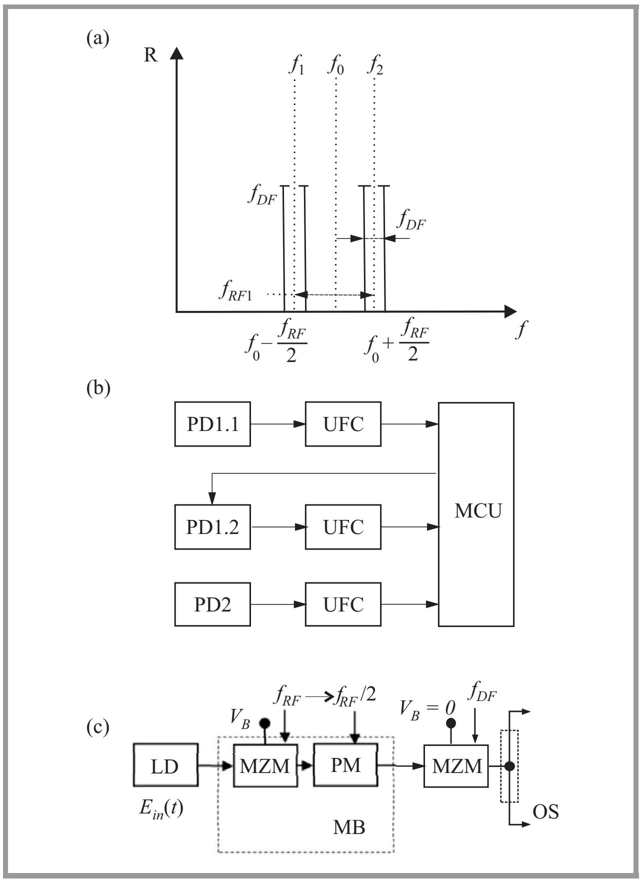

Fig. 4. MSRSIP test circuit for increasing the sensitivity of measurements in the field of high measured frequency: (a) spectral representation, (b) block diagram of a receiver part, (c) block diagram of a transmitter part.

The measurement sensitivity was 3-6 times improved as compared to direct detection method in the frequency band. The impact of photodetectors flicker noise on the accuracy of amplitude measurements was reduced.

Block diagram of developed radio photonic MSRSIF at a level of modulation conversion is shown in Fig. 4c. It differs from circuit shown in Fig. 2a, having the second amplitude MZM operating in a mode of suppression of the carrier frequency in the zero point. A imitating modeling of proposed methods is provided in the application package OptiSystem simulated in OptiGrating 4.2.

The improvements of functional parameters were confirmed by the results of theoretical research and by developed radio photonic MSRSIF, which takes into account benefits of the all developed methods.

Measurement of the instantaneous frequency in a lower band of radio frequencies (VHF and UHF) requires the use of FBG with of ultra-narrow bandwidth, for example with a phase shift and providing stable working conditions in high temperatures.

4. Conclusions

The analysis of information on existing and prospective radio photonic MSRSIF with a measurement conversion amplitude-frequency in FBG, allowed to improve their metrological and technical and economic characteristics. The paper show that a further development of these systems may be based on the use therein AFMT of optical carrier, for measuring the instantaneous frequency, and to provide a stable operating mode of conversion devices.

The used AFMT of optical carrier to symmetric dual-frequency radiation, by splitting its components to a fixed difference frequency, located in the region of minimal noise of photodetector, with dual-band frequency-amplitude measurement conversion in FBG and a special form of optoelectronic conversion in narrowband photodetector, allowed to:

- twice extension of MSRSIF band,
- increasing the resolution of the measurements in the field of low frequency to the level of 0.8–1 GHz/dB,
- increasing measurement sensitivity by 3–6 times compared with the broadband photodetection,
- reducing the impact of low-frequency fluctuations in the amplitude accuracy.

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Aydar Revkatovich Nasybullin – for biography, see this issue, p. 102.