

Acousto-optic frequency shift oscillator

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For the first time, the operation of an optoelectronic oscillator with an integrated acousto-optic modulator has been demonstrated. The inclusion of the modulator in the feedback loop allows to generate an optic frequency shift in self-oscillatory mode without using a high-frequency oscillator. The dependence of the generation modes on the power of the laser radiation and the temperature of the modulator chip has been studied. The generation of the optic frequency shift of 171.5–174.5 MHz with the ability to adjust by changing the temperature of the modulator chip is demonstrated. The conditions for the emergence of a multi-frequency generation mode and the transition to chaotic oscillation generation have been determined.

Keywords: acousto-optic modulator, optic frequency shift, optoelectronic oscillator.

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Optical frequency shift is widely used in precision optical measurement systems such as coherent reflectometers [1] and heterodyne interferometers [2]. Optical frequency shift producing generally uses acousto-optic modulators (AOM) excited by radio-frequency oscillators set to a resonance frequency corresponding to the maximum optical radiation diffraction with a specified traveling acoustic wavelength with a period defined by the speed of sound in the modulator material [3]. Fine-tuning the parameters of the acousto-optic diffraction resonance is a separate task considering high selectivity and temperature dependence of resonance frequency [4]. This work proposes an original optoelectronic oscillator (OEO) scheme allowing the optical frequency shift to be implemented in a self-oscillating mode without a radio-frequency oscillator. Besides its applied relevance, the work is of scientific interest as the first demonstration of an optoelectronic oscillator with integrated AOM.

A circuit of the self-excited optical frequency shift oscillator (Figure 1) is a classical OEO configuration [5–7]. Optical part of the circuit contains an optical light source: a single-frequency semiconductor distributed feedback laser diode (DFB-LD) with a linear polarized optical output based on a birefringent polarization-maintaining fiber (PMF).

Linear polarized radiation is applied to the key circuit component input — integrated frequency-shift acousto-optic modulator (AOM). Its design was described in detail in our previous works [8,9]. Modulator operating principle is based on associated anisotropic diffraction on travelling surface acoustic wave (SAW) causing polarization rotation and optical radiation frequency shift. For AOM on the basis of an optical waveguide on a lithium niobate substrate, frequency shift is about 170 MHz [8,9] and is defined by dispersion properties of SAW and polarization mode dispersion (propagation constant difference between the orthogonal TE and TM eigenmodes). PMF axes at the AOM

input are oriented such that optical radiation of DFB-LD linearly polarized along the slow axis is input into the TE polarization mode of AOM. To increase polarization extinction, a thin-film plasmon-polariton polarizer was formed at the AOM input [10]. SAW is excited when a modulation signal is applied to an interdigitated transducer (IDT) via the AOM's electrical radio-frequency input. SAW propagation is codirectional with optical radiation propagation via the channel waveguide. The length of interaction between optical radiation and SAW is about 16 mm, which ensures the Bragg form of diffraction and high diffraction efficiency. A 45 mW high-frequency signal applied to IDT provided 100 % diffraction efficiency and full conversion of a linearly polarized input TE mode into an orthogonal output TM mode [9]. Bragg form of diffraction also provides high frequency selectivity of acousto-optic resonance (~ 240 kHz) [9], therefore to ensure stable operation of AOM and avoid the temperature drift, an integrated optical chip was mounted on a Peltier element and fitted with a thermistor for temperature measurement and stabilization.

There are generally both polarization modes of the waveguide at the AOM output: diffracted frequency-shifted optical radiation in the TM polarization mode and transmitted non-diffracted radiation in the TE polarization mode. PMF axes at the AOM output are oriented so that the TM mode is output into the fast axis and the TE mode is output into the slow axis, i.e. radiation at the fundamental and shifted optical frequency propagates as non-interacting orthogonal polarization modes.

Special aspects of the use of AOM as part of OEO are described below. High diffraction efficiency typical of the integrated AOM makes the self-oscillating mode excitation of optical frequency shift oscillation much easier. Due to high spectral selectivity of Bragg diffraction, the integrated AOM also performs a frequency filter function along with the electric-to-optical signal conversion function (modula-

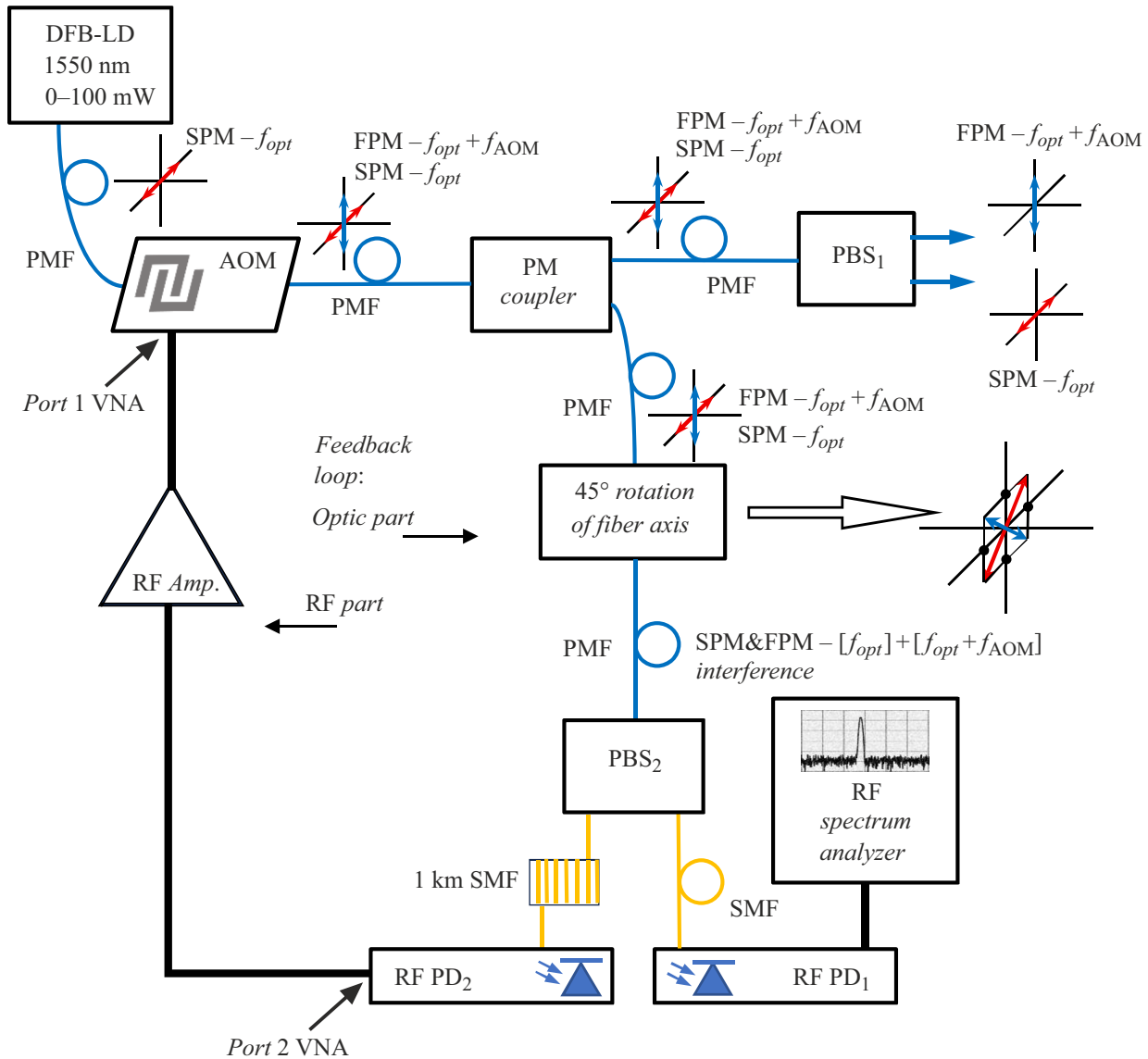


Figure 1. Self-excited optical frequency shift oscillator circuit. DFB-LD — laser (1550 nm, 0–100 mW), PMF — polarization-maintaining fiber, AOM — integrated acousto-optic modulator, PM coupler — polarization-maintaining optical coupler, PBS — polarization beamsplitter, 45° rotation of fiber axis, 1 km SMF — 1 km of standard single-mode optical fiber, RF PD — radio-frequency reverse biased photodiode, RF Amp. — RF amplifier (10–670 MHz, 28 dB), Port 1 VNA — connection of vector network analyzer port 1, Port 2 VNA — connection of vector network analyzer port 2, RF spectrum analyzer.

tion signal transfer to the optical carrier). Distributed diffraction process induces complex dynamic patterns of the filter amplitude and phase curves, which are defined by the modulation signal autocorrelation function with a time lag of $5\mu\text{s}$ (SAW propagation time along the interaction length). Thus, this type of modulators can provide new under-investigated feedback modes [11,12].

A polarization-maintaining optic power coupler (PM coupler) with a countdown ratio of 50/50 (3 dB) is installed downstream of AOM in the OEO circuit. One PM coupler output is an optical output of the self-excited frequency shift oscillator, an optical polarizing beam splitter (PBS₁) was additionally installed in it and optical radiation was split into frequency-shift and non-frequency-shift radiation.

The second PM coupler output is used in the optical part of the OEO feedback loop. PMF at the PM coupler output is welded there to PMF at the second optical polarizing beam splitter (PBS₂) input with axes rotated at 45°, which induces common amplitude projections of frequency-shift and non-frequency-shift optical radiation to new rotated fast and slow axes and conversion of frequency shift modulation to intensity modulation as a result of beating after passing through PBS₂ (demodulation). Optical radiation from one PBS₂ output is applied to a photodiode on the basis of radio-frequency reverse-biased photodiode (RF PD₁) that serves as the OEO's electrical output and is used for monitoring radio-frequency signals. The second PBS₂ output is connected to a non-polarization-maintaining standard single-

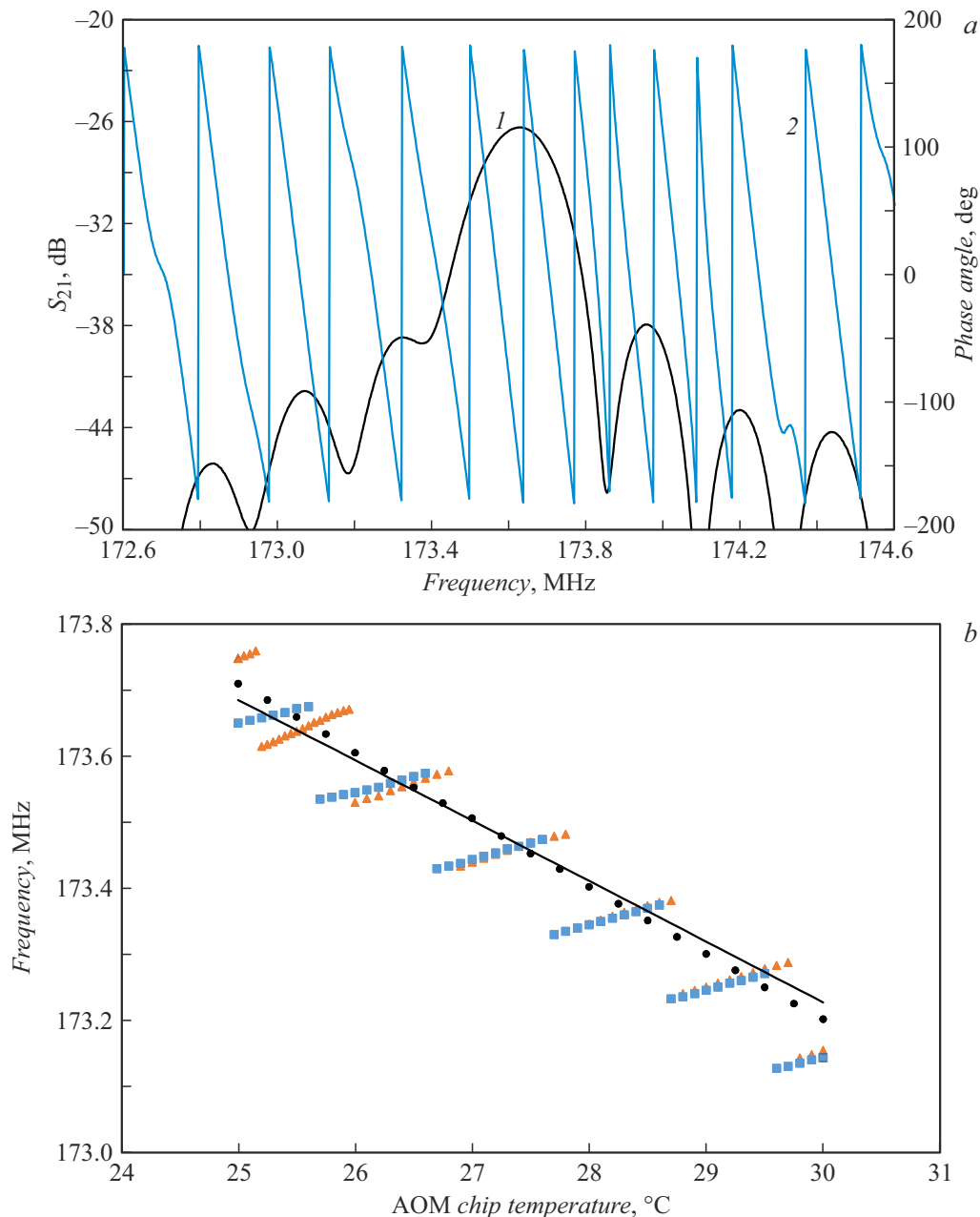


Figure 2. *a* — frequency dependence of the transmission coefficient with an open FB loop: 1 — amplitude, 2 — phase. *b* — oscillation frequency tuning in OEO single-frequency self-oscillating mode with AOM chip temperature variation (triangles — temperature rise, squares — temperature drop) and temperature dependence of the acousto-optic diffraction resonance peak with an open FB loop (solid line — theoretical curve [4], circles — experimental points).

mode optical fiber (SMF) coil with a length of about 1 km, which serves as an optical delay line to ensure low phase noise level of produced signals. A photodetector on the basis of a radio-frequency reverse-biased photodiode (RF PD₂) is also provided at the optical line end.

Electric signal from the RF PD₂ output is sent via a radio-frequency amplifier to the AOM's electrical input, thus, closing the OEO feedback (FB) loop.

Two conditions shall be fulfilled to excite self-oscillations: transmission coefficient with full loop bypass shall be larger

than 1 (0 dB), full phase shift shall provide positive feedback conditions.

The first experimental study stage involved the measurement of circuit transmission coefficient in the OEO FB open loop conditions. A signal was applied to the AOM's electrical input from the radio-frequency (RF) oscillator and detected using RF PD₂. Vector network analyzer was used for measurements. Dependence of the transmission coefficient (S_{21}) on the RF signal frequency at the fixed wavelength (1550 nm), DFB-LD power (8 mW) and fixed AOM temperature (25 °C) is shown in Figure 2, *a*.

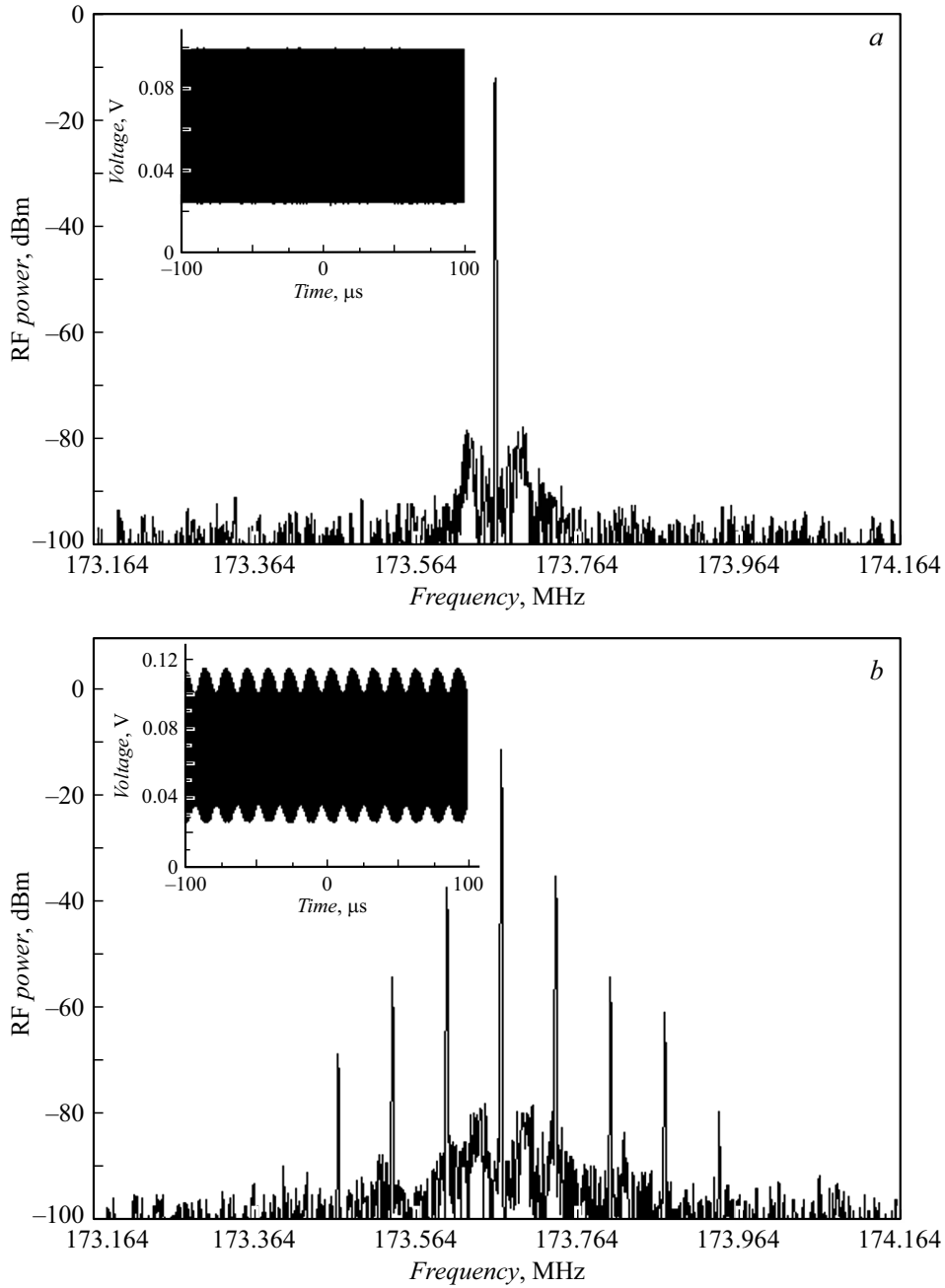


Figure 3. *a* — single-frequency oscillation mode: wavelength 1550 nm, temperature 25 °C, $P_{opt} = 8$ mW. *b* — multi-frequency oscillation mode: wavelength 1550 nm, temperature 25 °C, $P_{opt} = 15$ mW. *c* — chaotic oscillation mode: wavelength 1550 nm, temperature 25 °C, $P_{opt} = 87$ mW. Insets show oscilloscope waveforms from the photodetector output showing the envelope shape in different oscillation modes.

Transmission coefficient frequency dependence follows the acousto-optic diffraction resonance peak with a width of about 240 kHz.

Central frequency of the diffraction resonance peak by SAW can be tuned through AOM temperature or laser radiation wavelength variation [4]. Tuning is defined by dependences of SAW velocity on temperature and birefringence of lithium niobate crystal on temperature and light wavelength and is -0.1 MHz/°C and -0.12 MHz/nm, respectively [4]. Resonance frequency range tuning will be limited by the

effective SAW excitation frequency band defined by the IDT configuration [8,9]. AOM chip temperature could be set using the Peltier element within 15–45 °C, which ensured resonance frequency tuning within 171.5–174.5 MHz. The circuit used DFB-LD with a limited wavelength tuning range (~ 1 nm), which limited resonance frequency tuning in the range of about 120 kHz, which didn't exceed the acousto-optic diffraction selectivity (~ 240 kHz). Therefore, oscillation frequency tuning via light wavelength variation was not implemented. However, this mechanism can be

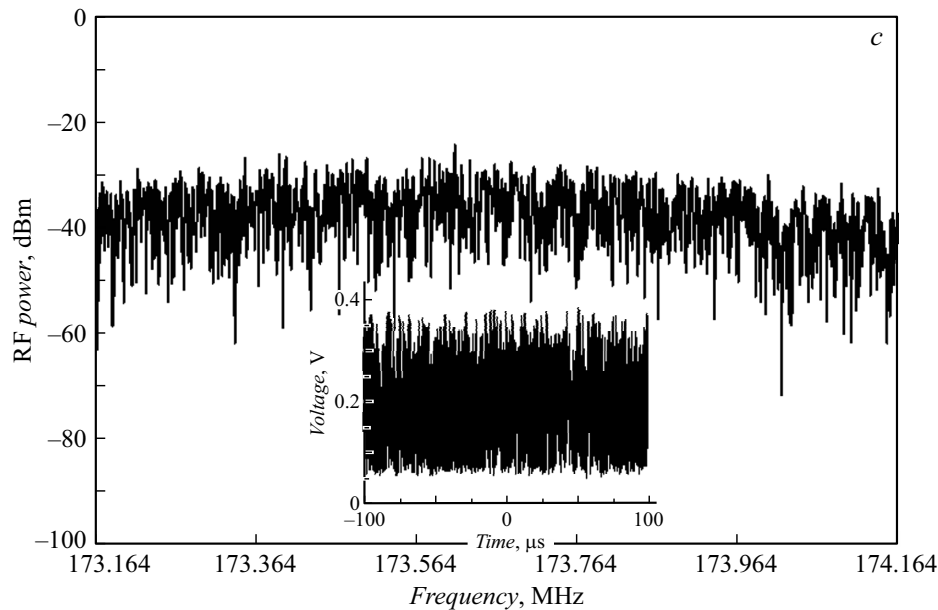


Fig. 3 (Contd).

also used for oscillation frequency tuning using a widely-tunable laser source.

In self-oscillating mode excitation experiments, the OEO FB loop was closed via the RF amplifier with a 10–670 MHz frequency band and transmission coefficient of 28 dB, then laser radiation power was gradually increased. RF signal spectrum at the RF PD₁ output was detected using an RF spectrum analyzer and the oscillated RF signal envelope shape was controlled using a digital oscilloscope. Frequency shift producing was not observed at a laser radiation power less than 7 mW because OEO loop loss exceeded the amplifier gain. For laser radiation power of 7–13 mW, the RF spectrum contains only one line (Figure 3, *a*), which corresponds to upward shift in the optical frequency by the OEO oscillation frequency in the optical spectrum. A constant-amplitude RF signal is oscillated in this case (waveform in Figure 3, *a*). This line is effectively tuned by AOM temperature variation (Figure 2, *b*). Temperature dependence of the central frequency of the maximum AOM transmission coefficient is continuous and monotonic, which was demonstrated in the experiments for measurement of acousto-optic resonance vs. temperature with an open FB loop (Figure 2, *b*). Experimental points fit well the theoretical dependence calculated on the basis of literature data on temperature dependences of refraction indices and SAW velocity for X-cut lithium niobate [4]. Note that self-oscillation frequency is tuned in steps during continuous monotonic temperature variation. The magnitude of steps is about 140 kHz and coincides with the frequency spacing between OEO loop resonance frequencies (modes) corresponding to 2π crossing by the measured phase-frequency characteristic of the transmission coefficient with open FB loop. Hence, we conclude that tuning takes place as a jump between OEO modes.

As the laser power increases above 13 mW, the system switches to the multi-frequency oscillation mode (Figure 3, *b*). Additional frequency components appear in the RF spectrum. Oscillated frequencies don't meet the oscillation conditions at the OEO loop resonance frequencies (modes) from the measurements with an open FB loop, which is similar to experiments with OEO on a dual Mach–Zehnder modulator with double FB [13]. Gradual growth of laser radiation power induces new oscillation lines, while the oscillated frequency spectrum is extended and frequency difference between adjacent oscillation lines decreases. The RF signal envelope shape with increasing number of oscillated frequencies takes a complex nonharmonic form. Similar behavior was observed previously in experiments on OEO frequency capture of OEO based on bulk AOM [14].

Further increase in the optical power above 18 mW places OEO into chaotic oscillation mode (Figure 3, *c*), which is typical for self-oscillating systems with time delay and nonlinearity in the FB loop [15,16], including the given AOM-based OEO. Complex oscillation behavior of AOM-based OEO requires additional investigations, which are beyond the scope of this brief report. Here we only note those AOM features that affect the OEO oscillation behavior: dependence of AOM's spectral response curve on the modulation signal at the AOM input causes heavy nonlinearity of the FB loop and the distributed form of interaction between oscillated SAW and optical radiation produces additional time delay in the FB loop associated with the SAW propagation time ($5\mu\text{s}$).

Finally, note that an original self-excited optical frequency shift oscillator circuit was proposed using integrated AOM as part of OEO. Single-frequency self-oscillation mode experimentally demonstrated to ensure coherent shift of the

optical frequency without using an RF oscillator to send a signal to AOM. The system changes to self-oscillation mode when the threshold optical power (7 mW), which ensures the OEO FB transmission coefficient greater than 1 (0 dB), is exceeded. Note that the maximum interference contrast in the demodulator corresponds to the single-frequency oscillation mode, which suits interference measurement systems in the best way.

Possibility of produced shift frequency tuning by changing the AOM temperature is demonstrated. Tuning takes place in steps between eigen resonant frequencies (modes) of the FB loop, which are apart from each other by approximately 140 kHz at the selected fiber-optic delay line length (~ 1 km) and considering the delay in AOM.

With further increase in the laser radiation power, the system demonstrates complex behavior and goes first into the multi-frequency self-oscillation mode (with optical power above 13 mW) and then into the chaotic oscillation mode (with optical power above 18 mW).

Findings are interesting for building precision optical measurement systems such as coherent reflectometers and heterodyne interferometers. Coherent frequency shift and multi-frequency oscillation mode can be potentially used for frequency comb producing [17], and the chaotic oscillation mode can be used to build random-number generators [16,18].

Conflict of interest

The authors declare no conflict of interest.

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