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Microwave filter based on Lamb modes for optoelectronic generator

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Abstract. Experimental results for narrowband filter based on yttrium iron garnet film epitaxially grown on gadolinium gallium garnet substrate have been shown. The principle of operation of the filter is based on excitation of Lamb modes in the substrate. We demonstrated also that the use of single crystal diamond as a substrate will significantly reduce the phase noise of the designed optoelectronic microwave generator.

One of the advanced devices in microwave photonics [1] is a microwave generator. It belongs to a new class of high-stability oscillators that are capable to work at the frequency ranging from hundreds of megahertz up to several hundreds gigahertz [2].

The main advantage of the microwave generator in comparison with a traditional microwave generator is a possibility to compromise between the frequency tuning enhancement and phase noise minimization [3]. There are designs of the optoelectronic microwave generators with very low phase noise about -160 dBc/Hz at 10 kHz offset frequency [4-8]. The maximum frequency of generation is limited by the pass-band of optoelectronic components that have currently lying in the range of hundreds of gigahertz [4]. Well known that such performance characteristics are difficult to achieve by the ordinary microwave generators due to the fundamental limitations.

The schematic view of an optoelectronic microwave generator is shown in Figure 1. The generator has a ring circuit that consisted of the radiofrequency and optical paths [4]. Usually the optical path consists of a light-emitting diode, an electro-optical modulator, an optical fiber, and a photodetector. The main elements of the radiofrequency path are a microwave amplifier and a microwave filter. The microwave filter plays a key role in the circuit providing the required operating parameters of the optoelectronic generator.

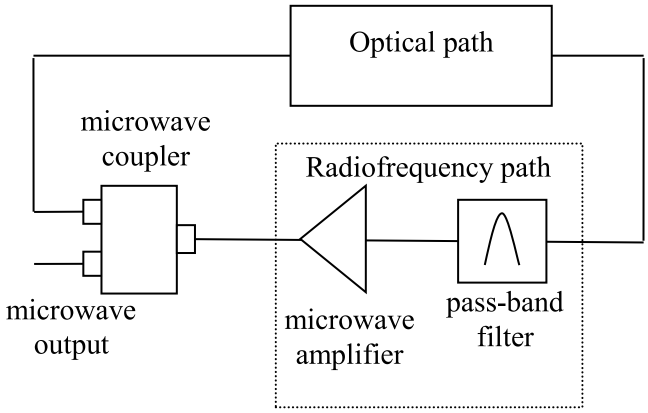

Figure 1. A block diagram of an optoelectronic generator.

Consider now the principle of operation of the ring circuit. The diode emits an optical carrier signal. Electro-optical modulator performs an amplitude-modulation of the optical signal by the microwave signal. That signal propagates through the optical fiber to the photodiode [8]. The optical fiber delays the signal. The delay time is determined by the length of optical fiber. An increase in time delay leads to an increase in the phase-frequency characteristic slope decreasing the phase noise of the generator. It was shown in [8] that the increase of optical fiber length from 100 m to 1000 m reduces the phase noise from -95 dBc/Hz to -107.57 dBc/Hz at 10 kHz offset frequency (Figure 2).

The photodiode receives the optical signal and demodulates it into the microwave signal. After demodulation the microwave signal propagates through the radiofrequency path. The microwave filter provides frequency selectivity and determines the generation frequency. In this case phase balance condition is

$$\varphi_{opt} + \varphi_e = 2\pi n, \qquad (1)$$

where φ_{opt} is a phase shift in the optical fiber, φ_e is a phase shift in electrical circuits, and n is a number of generation mode. In fact the optical fiber length significantly exceeds the length of the electrical circuits in radiofrequency path, i.e. phase shift in radiofrequency path circuits can be neglected $\varphi_e \approx 0$.

Time delay determines generation frequency by the phase balance condition generation frequencies become closer by increasing of time delay. Therefore, the requirement for narrow band microwave filter considerably increases. The microwave amplifier is used for compensation of loss. The equidistant spectrum of generation frequencies that carried out the phase balance condition is shown in Figure 3. Note that, the suppression level of the remaining harmonics determines the lowest possible phase noise of developed microwave generator.

It should be noted that the frequency of generated signal can be tuned in accordance with the bandwidth tuning of the tunable microwave filter. For example, the frequency tuning of the generated signal in the range from 6 to 12 GHz with a phase noise level of -128 dBc/Hz (at 10 kHz offset frequency) was demonstrated in [9]. The similar tuning can be achieved by the band-pass filter based on a film of yttrium iron garnet (YIG). The YIG-film filter operates due to the phenomenon of spin wave propagation.

The actual problem is to develop a high-Q band-pass microwave filter. The required high-Q (narrow-band) microwave filter can be realized using magnetoacoustic interaction. This interaction results in excitation of high-Q acoustic oscillations (Lamb modes) by the spin waves propagating in single-crystal YIG films [10 – 14].

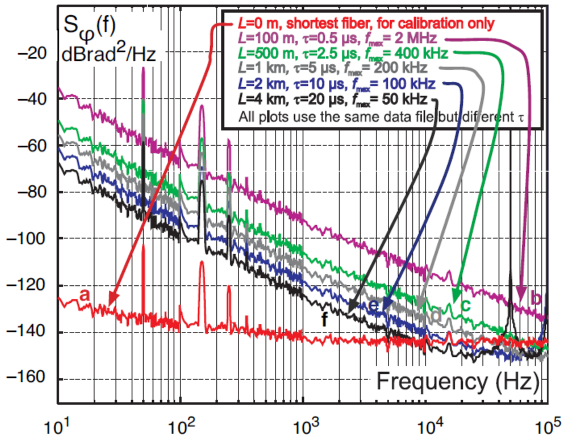

Figure 2. Dependence of the phase noise for different lengths of optical fiber [9].

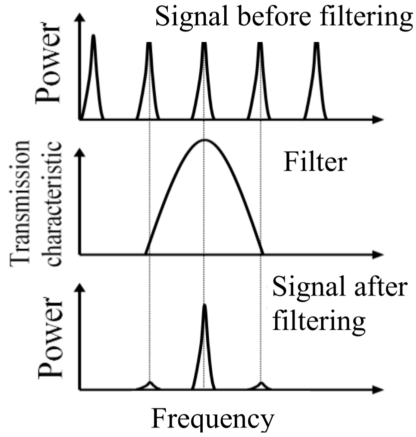

Figure 3. Equidistant spectra of optoelectronic generator; transmission characteristic of the microwave filter and the microwave signal after filtering.

Let us consider the operation and design of the band-pass magnetoacoustic filter for application as a frequency control element in optoelectronic generators. The experimental prototype used for the investigation of the magnetoacoustic oscillations is shown in Figure 4. The prototype was consisted of a 500-μm-thick single-crystal gadolinium gallium garnet (GGG) substrate with the 5.7-μm-thick YIG films epitaxially grown on the both sides of the substrates. The YIG film had a width of 2 mm, length of 30 mm, and a saturation magnetization of 1750 G. Ferromagnetic resonance linewidth was 0.5 Oe at 5 GHz frequency. The microwave microstrip antennas with length of 2 mm and width of 50 μm have been formed on alumina substrates metallized from back side. Thickness of the substrate was of 0.5 mm. This structure was magnetized with external magnetic field of 1938 Oe directed perpendicular to the surface of the YIG film that is the condition for the excitation of forward volume spin waves.

The antenna shown in Figure 4 as "Port 1" was exploited as the microwave input. It excited forward volume spin waves in YIG film. Antenna served as "Port 2" received the forward volume spin waves. It was the microwave output. The distance between the "Port 1" and "Port 2" antennas was 4 mm. Antenna denoted as a "Port 3" was used for the reception of spin waves excited from the other side of the GGG substrate. This antenna was positioned of 3 mm distance from the antenna "Port 1".

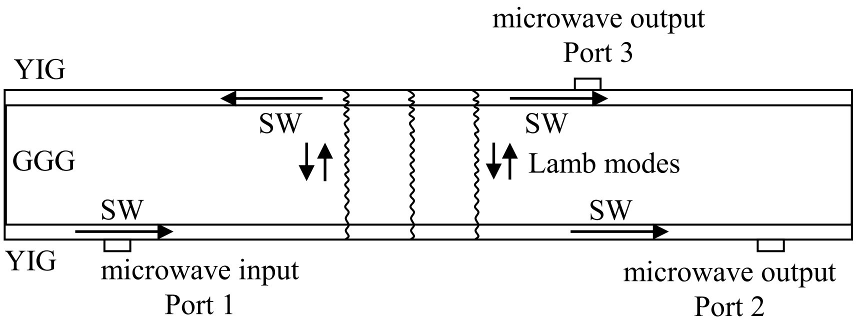

Figure 4. Prototype for the study of magneto-oscillations in the structure of the YIG / GGG / YIG.

Measured transmission characteristics S_{21} and S_{31} are shown in Figure 5. Dips on the S_{21} characteristic correspond to the excitation of Lamb modes by spin waves propagated along the "bottom" YIG film [12]. In turn, these Lamb modes propagated across the substrate GGG excite the forward volume spin waves in the "upper" YIG film. Note that the dips at amplitude frequency characteristic $S_{21}(f)$ are equidistant that confirms acoustic nature of these excitations.

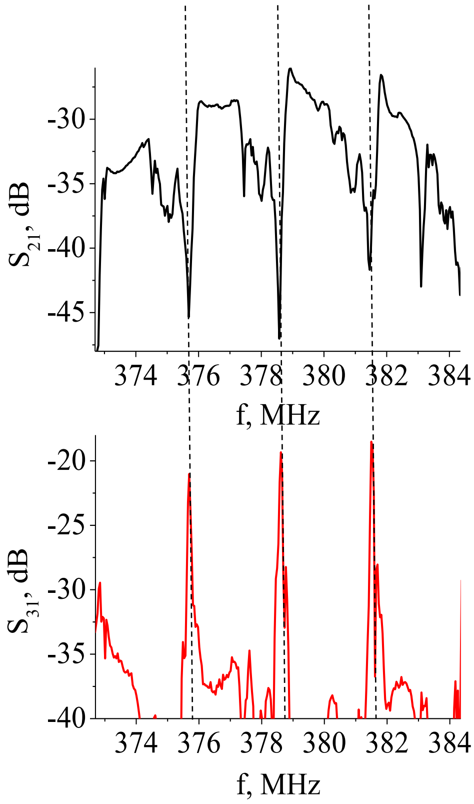

Figure 5. Experimental transmission characteristics S_{21} and S_{31}.

The S_{31} characteristic corresponds to the transmission characteristic of the developed narrowband filter. The quality factor Q is about 5000. Note that the obtained value of the Q-factor exceeds 5-10 times Q-factor of ordinary YIG-filter based on phenomenon of ferromagnetic resonance. One way to further increase of Q-factor is using instead GGG another material with better acoustic properties such as diamond. The acoustic properties of diamond and GGG are shown in Table 1.

Table 1.

	Diamond [15]	GGG [16-17]
Young's modulus	1050 GPa	222 GPa
Poisson's ratio	0.1	0.28
Speed of sound	17500 m/s	3521 m/s

One can see that Young's modulus of diamond higher than of GGG. Therefore the use of single-crystal diamond substrate instead of GGG allows to increase the Q-factor [18]. It will significantly reduce the phase noise of the designed optoelectronic microwave generator.

In conclusion, the design of band-pass magnetoacoustic filter based on Lamb modes for application as a frequency control element in optoelectronic generators was considered. The experimental prototype was fabricated and experimental transmission characteristics were measured. The Q-factor was about 5000. It was shown that the use of single crystal diamond as a substrate will significantly reduce the phase noise of the designed optoelectronic microwave generator.

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