

## Spin-wave band-pass filters based on yttrium iron garnet films for tunable microwave photonic oscillators

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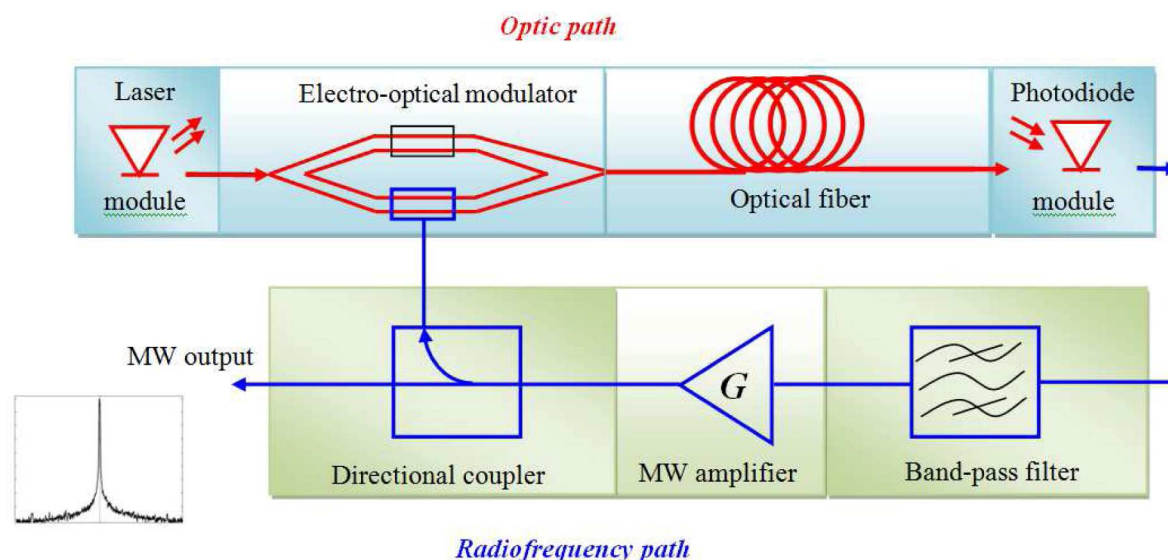
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**Abstract.** The paper reports on development of tunable band-pass microwave filters for microwave photonic generators. The filters were fabricated with the use of epitaxial yttrium iron garnet films. Principle of operation of the filters was based on excitation, propagation, and reception of spin waves. In order to obtain narrow pass band, the filtering properties of excitation and reception antennas were exploited. The filters demonstrated insertion losses of 2-3 dB, bandwidth of 25-35 MHz, and tuning range of up to 1.5 GHz in the range 3-7 GHz.

Elaboration of microwave signal generators has always been an urgent problem. In recent years, a great interest for development and research of microwave photonic oscillators is evident. The main advantage of the microwave photonic oscillator compared to conventional ones is to overcome the trade-off between the oscillator frequency tuning range and the phase noise level [1]. To date, the microwave photonic oscillators with extremely low phase noise level exist [2-5]. For example, the oscillator developed in work [6] has the phase noise level of -140 dBc/Hz at 10 kHz offset from the carrier. Note that a similar phase noise level is practically unachievable for common microwave generators. Besides in recent years the upper frequency limit of the microwave photonic generators was increased up to hundreds of gigahertz [2,7,8].

A typical microwave photonic oscillator is a ring circuit which includes microwave and optical parts (see figure 1). In the simplest case, the optical part of the generator consists of a laser module, an electro-optic modulator, an optical fiber, and a photo-detector. The main elements of the microwave part include a microwave amplifier and a microwave band-pass filter. As was already mentioned above, an advantage of the microwave photonic generator is a significant reduction of the phase noise level, which depends on the length of the optical fiber. For example, it is shown in work [9] that increase in the fiber length from 100 m to 1000 m reduces the phase noise level from -95 dBc/Hz to -107 dBc/Hz at 10 kHz offset. However, it is clear from the condition of the phase balance that a frequency spectrum of the generator is a series of equally spaced generation frequencies. Thus, the distance between the generation frequencies for the length of the optical fiber of 10 m is about 30 MHz, and for the length of 100 m is 3 MHz. From this follows that in order to select a specific generation frequency it is necessary to use a narrowband band-pass microwave filter. Such a filter must be electronically tunable in order to realize electronic tuning of the generation frequency. Thus, the band-pass microwave filter *plays a key role* in obtaining the desired performance characteristics of the microwave photonic generator.





**Figure 1.** Schematic illustration of microwave photonic oscillator.

It is known from the literature that several types of the filters are commonly used for the frequency filtering in the microwave photonic oscillators. They are cavity resonators [10], Fabry-Perot resonators [10], optical ring resonators [12], as well as whispering gallery mode resonators [6,13]. Actually, a commercial version of the integral microwave photonic generators based on the whispering gallery resonators has been developed by OEwaves, Inc. ([www.oewaves.com](http://www.oewaves.com)). The phase noise level of this generator was -108 dBc/Hz at 10 kHz offset. We note that a disadvantage of all above mentioned generators is that they are not tunable.

One of the most effective methods to develop a tunable microwave filter and, therefore, a tunable optoelectronic microwave generator is to utilize for filtering purposes microwave waves travelling in ferromagnetic films and/or in ferrite-ferroelectric structures. Utilization of the travelling waves (spin waves and spin-electromagnetic waves) in the electronically tunable materials for creation of microwave photonic devices was not studied before. On the other hand, ferrite materials (yttrium iron garnet spheres) have been probably used as microwave filters in microwave photonic circuits (see [14,15]). We wrote “probably” because there is no direct information about the types of the microwave filters in the papers [14,15].

Epitaxial single-crystal yttrium iron garnet (YIG) films as well as YIG spheres are used to create microwave devices for many years (see, e.g. [16] and references therein). An advantage of devices based on YIG films is their planar structure allowing to create the filter topology in a single technological cycle. It is more convenient for the production on an industrial scale. Therefore, an elaboration of the tunable YIG-film-based band-pass microwave filters is important task. A survey of the literature and the reviews on the microwave photonic oscillators brings an idea that a further improvement of such oscillators can be achieved with an application of microwave filters tunable in a wide frequency range.

We underline that the tunable YIG-film-based band-pass filters provide not only frequency filtering but a group delay time, which is rather big in comparison with common filters. Due to the principle of operation of the film-based filters the time delay is obtained through travelling of the spin waves. In other words, spin-wave filter has a steep phase-frequency characteristic. Such steepness may be comparable or even bigger than corresponding steepness introduced in the loop circuitry of microwave photonic oscillator by an optical fiber. It is clear physically that this spin-wave effect should lead to a reduction of phase noise level of a microwave photonic generator.

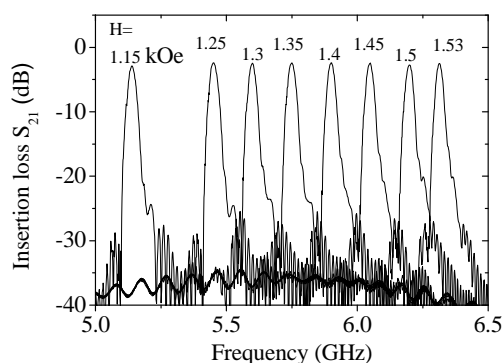
This work reports on development of the YIG-film band-pass filters as frequency selective elements of microwave photonic oscillators. The main goal of the work was elaboration of the filter

design providing small insertion loss for microwave signal in relatively narrow pass band because a phase noise of the oscillators is determined by the loss in addition to the time delay. It was also important to achieve relatively broad frequency tuning range.

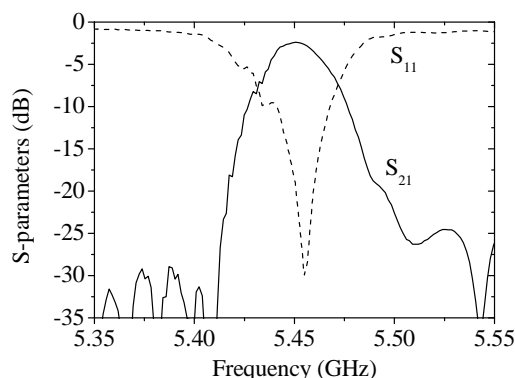
The filter was designed as a delay line with excitation and reception antennas. An yttrium iron garnet film was utilized in the structure as a spin-wave waveguide. The YIG film was grown on gadolinium gallium garnet substrate by method of liquid phase epitaxy. The film had a thickness of 9  $\mu\text{m}$  and a saturation magnetization  $4\pi M_s$  of 1750 G. The film was magnetized in its plane so as to provide a propagation of the surface spin waves. In order to obtain narrow pass band, the filtering properties of excitation and reception antennas were exploited. For this the original topology of the antennas was designed. The experimental prototype was positioned between the poles of electromagnet for characterization.

Amplitude-frequency characteristics (AFCs) of the filter measured for different values of bias magnetic field  $H$  are shown in figure 2. Typical frequency dependences of the insertion loss  $S_{21}$  and the return loss  $S_{11}$  for  $H = 1250$  Oe are shown in figure 3. The measurement results show that the frequency tuning range of the filter was of 5140-6320 MHz. The tuning was provided with variation of the bias field in the range of 1150-1530 Oe. In this frequency range the minimum insertion losses were of 2.4-2.9 dB (see figure 4) and return losses were more than 20 dB. The filter bandwidth measured at -3 dB from minimum insertion loss was 28-34 MHz. The steepness of the slopes of AFC from outside the pass band was varied in the range of 0.7-3.8 dB/MHz. The delay time was of 22 ns.

The experimental filter prototype did not use any additional elements that increase the isolation between input and output. Therefore, the out-of-band attenuation was relatively low, in the 35-40 dB. Low-frequency and high-frequency parasitic pass bands are more than 20 dB below the minimum insertion loss.



**Figure 2.** Amplitude-frequency characteristics of the YIG-film filter for  $H = 1150$ -1530 Oe.

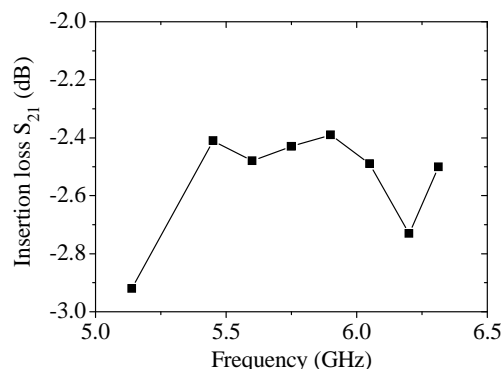


**Figure 3.** S-parameters of the filter for  $H = 1250$  Oe.

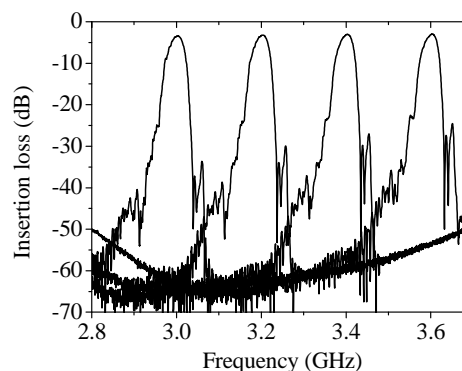
It is known that YIG-film filters designed for operation at microwave power of tens to hundreds of milliwatts have a low-frequency limit of tuning. This is due to the existence of low-frequency three-magnon decay of spin waves at such power levels [18]. For YIG films with the saturation magnetization of 1750 G the spin waves decay below 3.2 GHz frequency in the entire spectrum of spin waves. In the range of 3.2-4.9 GHz spin waves demonstrate the decay only in high-frequency part of the surface spin wave spectrum. Therefore, such films are typically used in filters for frequencies above 4.5 GHz. To design the filter for lower frequencies, it is appropriate to use substituted epitaxial YIG films having reduced saturation magnetization. For such films a boundary of the three-magnon decay occurs at the lower frequencies.

Figure 5 shows AFCs of the filter developed with the substituted YIG film having a saturation magnetization of 800 G. The bias field variation in the range of 710-930 Oe resulted in the tuning of the centre frequency in the range of 3-3.6 GHz. The filter bandwidth was of 35 MHz. To increase the

isolation between the input and output antennas, special metal screens were used. The delay time was of 29 ns.



**Figure 4.** Minimum insertion loss versus frequency characteristic.



**Figure 5.** Amplitude-frequency characteristics of the filter made with substituted YIG film for  $H = 710-930$  Oe.

In conclusion, the developed tunable microwave band-pass filters based on epitaxial YIG films demonstrated relatively low insertion loss on the order of 2-3 dB and relatively narrow bandwidth on the order of 30 MHz. These values look favorable in comparison with already existing YIG-film filters [17-21]. The results show that our developed filters have great potential for application. They can be used for development of *tunable* microwave photonic devices, in particular, oscillators. The filters can find conventional application also in microwave equipment.

### Acknowledgments

This work was supported in part by the Russian Foundation for Basic Research, Grant of President of the Russian Federation, and by Ministry of Education and Science of the Russian Federation (Project "Goszadanie").

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