Magnetically tunable high-Q spin-wave optoelectronic single-loop resonator

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Abstract. Resonant properties of a spin-wave optoelectronic single-loop resonator are experimentally investigated. The resonator is composed of a spin-wave delay line and a microwave photonic delay line based on a single-mode optical fiber. This circuit is equivalent to a comb filter. The microwave photonic delay line provides the main contribution to the delay time and defines mostly the free spectra range (FSR). The spin-wave delay line realizes the reconfiguration of resonator bandwidth and its frequency tuning. Influences of delay time and amplifier gain coefficient on quality-factor are analyzed.

Increase in total bandwidth of microwave devices is one of the strictest demands to modern communication systems. Microwave photonics based on combination of electric and photonic circuitries provides practical methods for achievement of subterahertz bandwidth [1, 2, 3]. The use of the photonics and the functional electronics in the same device provides enhancement of functionality and performance characteristics of the device. One of the examples of microwave photonic circuits is closed-loops with delay lines (DLs) which demonstrate wide variety of effects. Closed-loop circuit consisting of series connected active or passive microwave photonic DL and spin-wave DL realize classical configuration of the spin-wave OEO.

Closed-loop circuits with DL operate in two modes due to active or passive regime. The active regime leads to self-oscillations and the circuit operates like an oscillator. Spin-wave optoelectronic oscillators (OEOs) are demonstrative example of the enhancement. It combines advantage of low phase noise of OEOs [4] and wide magnetic tuning of spin-wave devices [5, 6]. In the case of passive regime, losses in the DL exceed the amplification that leads to saturation and the circuit operates like a resonator. Closed-loop circuit with passive regime is called an active ring resonator (ARR). The frequency response of the ARR has a comb shape with a pass bands corresponding to the resonant frequencies [7]. Position of the resonant frequencies is defined by geometry of the DL and a dispersion of the eigen-waves in it. The spin-wave DL is strongly dispersive therefore the frequency response is a function of its design parameters. Microwave photonic DL usually utilizes single-mode fibers with extremely low insertion losses that yield the delay times in the tens or even hundreds of microseconds and eventually extremely high quality factors.

The purpose of this work is the experimental investigation of the frequency response of a spin-wave optoelectronic single-loop resonator based on cascade connection of the spin-wave and microwave photonic DLs.

The block diagram of the spin-wave optoelectronic single-loop resonator experimental prototype is shown in Fig. 1. This resonator is a typical ARR.
Fig. 1. A block diagram of the spin-wave optoelectronic single-loop resonator

The resonator is a closed-loop circuit consisting of microwave photonic and spin-wave DLs. Microwave photonic delay line is formed by a semiconductor laser (1) continuously emitting at a wavelength of 1.55 μm, the intensity electro-optical modulator (2) of Mach-Zehnder type with a bandwidth of 20 GHz, the single-mode optical fiber (3) with various lengths \( l_{\text{opt}} \), and a high-speed photodetector (4) with the bandwidth of 25 GHz. Spin-wave DLs (5) is based on various YIG films with variety of antenna geometries. Two identical microwave amplifiers (6) are used for circuit losses compensation. The amplifiers demonstrate 1 dB suppression at output power of 30 dBm. The gain of each amplifier is 32 dB. These values were almost constant in the nominal frequency range of 4-9 GHz. The ring gain is regulated by a variable attenuator (7). Input and output of a microwave signal is carried out by directional couplers (8) and (9) with a couple coefficient of –10 dB.

The investigated resonator operates as follows. A test microwave signal with frequency \( \omega_{\text{mw}} = 2\pi f_{\text{mw}} \) is supplied through the directional coupler (9) to the microwave photonic DL. It accumulates delay time \( \tau_{\text{opt}} = l_{\text{opt}} n / c \), where \( l_{\text{opt}} \) is a length of optical fiber, the \( n \) is its refractive index, \( c \) is the speed of light in vacuum. The phase shift of the microwave signal in microwave photonic DL is \( \Phi_{\text{opt}} = k_{\text{opt}} l_{\text{opt}} \), where \( k_{\text{opt}} \) is a wave-number of the signal envelope, which is equal to \( k_{\text{opt}} = \omega_{\text{mw}} n / c \). After microwave photonic DL the microwave signal is fed in the spin-wave DL accumulating the delay time \( \tau_{\text{sw}} = l_{\text{sw}} / V_g \), where \( l_{\text{sw}} \) is the propagation path that is equal to the distance between the antennae, \( V_g \) is the group velocity of the spin wave in YIG film. The phase shift in spin-wave DL is \( \Phi_{\text{sw}} = k_{\text{sw}} l_{\text{sw}} \), where \( k_{\text{sw}} \) is wavenumber of spin waves at a frequency \( f_{\text{mw}} \). The signal is amplified and supplied to the input of the microwave photonic DL. Thus the loop is closed and the microwave signal starts circulating in the circuit.

The resonance condition in the loop is determined by phase balance \( \Phi_{\text{opt}} + \Phi_{\text{sw}} + \varphi_{\text{e}} = 2\pi m \), where \( \varphi_{\text{e}} \) is phase shift in the electronic interconnections, which is usually small as compared with \( \Phi_{\text{opt}} \) and \( \Phi_{\text{sw}} \) and \( m \) is an integer number. The value of transfer coefficient is defined by values of insertion losses introduced by DLs and a value of amplifier gain coefficient. Damping decrement of the signal in microwave photonic DL is defined by losses in fiber, modulator, and photodetector. Single-mode fiber damping decrement is approximately \( \alpha_{\text{opt}} = 0.2 \text{ db/km at } 1.55 \mu\text{m} \). However, in experiment series the power loss of the microwave signal between electro-optical modulator input and the photodetector output was about -50 dB. This value was almost constant in the frequency range of 4-9 GHz. Contrariwise, the transfer coefficient of the signal in spin-wave DL is defined by the antennae geometry and damping decrement that is \( \alpha_{\text{sw}} = 2 \pi \mid g \mid \Delta H / V_g \), where \( \mid g \mid = 2.8 \times 10^{10} \text{ s}^{-1} \text{T}^{-1} \) is gyromagnetic ratio for electron and \( \Delta H \) is half of ferromagnetic resonance linewidth.

Basic application of ARR is the comb filters. In contrast to comb filters based on single microwave photonic DL introduction of additional spin-wave DL provides an opportunity to implement reconfiguration of frequency response. The FSR is defined by the delay time in the microwave photonic DL. The filter bandwidth is determined by the bandwidth of the spin-wave DL. Changing of
its design parameters allows varying of spin-wave DL bandwidth in the range from 10 MHz to 1.5 GHz. These parameters include the thickness of the YIG film, its saturation magnetization, external bias magnetic field, the geometry of the spin-wave antennae, as well as the distance between them and the distance between the antenna and the film surface.

At the first step, microwave photonic DL and spin-wave DL with close delay time values $\tau_{\text{opt}} \approx \tau_{\text{sw}}$ were chosen in order to demonstrate features of frequency response formation in the spin-wave optoelectronic single-loop resonator. The measured frequency response of the resonator in absence of the spin-wave DL for the case of fiber length $l_{\text{opt}} = 20$ m is shown in Fig. 2a by curve 1. One can see that the frequency response had a large number of resonant peaks corresponding to the eigen-modes of the closed-loop. Curves 2, 3, and 4 show the frequency responses of the spin-wave DLs with different design parameters. Curves 2 and 3 demonstrate frequency responses of DLs with YIG film thickness equal 16.9 $\mu$m (curve 2) and 5.4 $\mu$m (curve 3). Both these curves were measured in the case of two 50-$\mu$m-wide and 2-mm-long microstrip antennae. Curve 3 and 4 display the effect of application of two two-element antennae instead of single-element antennae. In experiment 50-$\mu$m-wide meander-type antennae with 160-$\mu$m distance between elements of each antenna were used. For all curves the distance between antennae $l_{\text{sw}}$ was 3 mm and bias magnetic field was $H_0 = 2090$ Oe.

![Figure 2](image_url)

**Figure 2.** Experimental frequency response characteristics of: single-loop resonator based on microwave photonic DL in absence of spin-wave DL and spin-wave DL on YIG film various thicknesses and antenna geometries (a); spin-wave optoelectronic single-loop resonator with spin-wave DL on YIG film with thickness of 16.9 $\mu$m and microstrip antennae (b), spin-wave DL on YIG film with thickness of 5.4 $\mu$m and microstrip antennae (c), spin-wave DL on YIG film with thickness of 5.4 $\mu$m and meander-type antennae (d).

As shown in the Figs. 2b, 2c, and 2d the resulting frequency response of the investigated microwave photonic resonator with spin-wave DL contains resonant peaks only within the bandwidth of the spin-wave DL. The FSR decreases in comparison with curve 1 due to additional delay time $\tau_{\text{sw}}$ introduced by the spin-wave DL. Decrease of the film thickness provides higher delay time and smaller FSR as it is shown in Figs. 2c and 2d. The change of antenna geometry offers an additional feature of the frequency response reconfiguration. Fig. 3 represents the tuning of the resonant frequencies by variation of the bias magnetic field in the range from 1990 Oe to 2090 Oe. These characteristics were measured for the case of spin-wave DL made of 5.4-$\mu$m YIG film with microstrip antennae and microwave photonic delay line with length of 20 m.
Figure 3. Magnetic tuning of experimental frequency response of the spin-wave optoelectronic single-loop resonator

Frequency response of the spin-wave optoelectronic single-loop resonator with increased distance between spin-wave antennae $l_{sw}$ up to 4 mm is shown in Fig. 4(a). Fig. 4b demonstrates the effect of increase of optical fiber length up to 60 m. One can see that the increase of delay time provides decrease of the FSR and increase of quality factor. While the delay time in spin-wave DL is limited by an acceptable level of insertion losses -20-30 dB/µs, the delay time in microwave photonic DL achieves hundreds of microseconds.

Figure 4. Experimental frequency response characteristics of spin-wave optoelectronic single-loop resonator based on the spin-wave DL with 4 mm distance between spin-wave antennae and microwave photonic DL with fiber length of 20 m (a) and 60 m (b)

As a second step, spin-wave optoelectronic single-loop resonators with delay time of the microwave photonic DL that is much higher than in the spin-wave DL $\tau_{opt} \gg \tau_{sw}$ were analyzed. It is clear that contribution of the delay time of the microwave photonic DL to total delay time increases with the increase of optical fiber length. For condition $\tau_{opt} \gg \tau_{sw}$ the FSR is defined by delay time in the microwave photonic DL. The decrease of contribution of spin-wave delay time in FSR due to increase of optical fiber length is shown in Fig. 5, where $FSR_{opt}$ is FSR of the resonator based on spin-wave and microwave photonic DLs and $FSR_{opt}$ is FSR of resonator measured in absence of spin-wave DL. The operation frequency for Fig. 5 is 8.15 GHz. Therefore, the spectrum of resonant frequencies in the investigated resonator based on spin-wave and microwave photonic DL becomes equidistant at fiber length more than 1000 m.
Figure 5. Dependence of relative FSR on optical fiber length

Fig. 6a shows the fragments of frequency responses measured for different optical fiber length. Fig. 6b shows the dependence (black line) of the equivalent quality factor $Q$ of the resonant peak with minimum losses on the ring gain $G$ in the case of fixed optical fiber length $l_{opt} = 600$ m and dependence (blue line) of the equivalent quality factor $Q$ of the resonant peak on fiber length $l_{opt}$. It is evident that the quality factor increases with increasing $l_{opt}$ and $G$ and achieve the several tens of thousands. Note that $G = 0$ is self-oscillation threshold that limited the values of Q-factor in practice.

Figure 6. Series of single resonant frequency response (a), dependence of the equivalent quality factor $Q$ of the resonant peak with minimum losses on the ring gain $G$ in the case of fixed optical fiber length $l_{opt} = 600$ m and dependence of the equivalent quality factor $Q$ of the resonant peak on fiber length $l_{opt}$ (b)

In conclusion, the frequency response of spin-wave optoelectronic single-loop resonator is reconfigurable. The bandwidth is defined by YIG-film thickness and geometry of antennae. FSR is defined by delay time in spin-wave and microwave photonic delay lines. Increase of optical fiber length provides frequency comb spectrum in bandwidth allowed by spin-wave delay line. Change of bias magnetic field realizes frequency tuning. Quality factor increases with increase of ring gain and fiber length and archives tens of thousands. Performance of described resonator corresponds to reconfigurable tunable comb filter.
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