Yttrium Iron Garnet-Based Combinatorial Logic and Memory Devices

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ABSTRACT Yttrium iron garnet $Y_3Fe_2(FeO_4)_3$ (YIG) has a uniquely low magnetic damping for spin waves, which makes it a perfect material for magnonic devices. Spin waves typically exist in the microwave frequency range, and their wavelength can be decreased to the nanoscale. Their dispersion in YIG waveguides depends on the strength and orientation of the bias magnetic field. It may be possible to exploit YIG waveguides as field-controlled filters and delay lines. In this work, we describe combinatorial logic and memory devices to benefit YIG properties. An act of computation in the combinatorial device is associated with finding a route connecting the input and output ports. We present experimental data demonstrating the pathfinding in the active ring circuit with YIG waveguide. The ability to search in parallel through multiple paths is the most appealing property of combinatorial devices. Potentially, they may compete with quantum computers in functional throughput.

INDEX TERMS Circuits and systems, logic devices, magnetic circuits.

I. INTRODUCTION

Magnonics is the field of spintronics concerned with structures, devices, and circuits that use spin currents carried by magnons [1]. Magnons are the quanta of spin waves: the dynamic eigen-excitations of a magnetically ordered body. Spin waves can be utilized for carrying and processing information in magnetic-wave-based devices [2]. Spin-wave logic devices are one of the promising approaches toward chargeless circuitry free from the drawbacks inherent to modern electronics, such as dissipation of energy due to ohmic losses. There are several unique physical properties inherent to spin waves to be implemented for data processing. First, a spin wave is a collective oscillation of spin in magnetic lattice. Spin waves are naturally confined within the magnetic media with no chance to escape or leak to nonmagnetic surroundings. It makes it possible to build a spin-wave bus for information transfer using magnetic wires similar to optical waveguides [2]. Second, spin-wave dispersion depends on the magnetic field. For instance, spin-wave transport through a magnetic waveguide is affected by the local distortion of magnetic field. This fact translates in the possibility of using spin waves for magnetic bit read-in and read-out [3]. Third, there is a robust and energy-efficient mechanism for spin wave to voltage and vice versa conversion using multiferroic cells [4], [5], [6]. This approach is of great importance for integrating spin-wave devices with conventional electronic components.

Fast amplitude damping is the major physical constraint of spin-wave devices based on conducting ferromagnetic materials. For instance, the damping time in permalloy is about of 1 ns at room temperature, which limits the propagation length to a few tens of micrometers [7]. However, this technical obstacle is overcome in ferrites—in particular, yttrium iron garnet (YIG) [8]. Spin waves in YIG may show relatively large (e.g., up to 1 cm) coherence length even at room temperature. It makes YIG the best material for spin-wave-based devices development. There has been a significant progress in YIG-based magnonic logic and memory devices prototyping during the past two decades. [9]. The utilization of phase in addition to charge demonstrated great potential in application to NP problems. For instance, prime factorization was accomplished using a spin-wave interferometer [10]. The abovementioned works encompass the road toward magnonic devices, which may complement CMOS in the special task data processing. A comprehensive review on the recent advances in spin-wave logic devices can be found in [11]. In this work, we present experimental data on recently proposed combinatorial logic devices in which an act...
of computation is associated with finding a path connecting input and output ports [12]. Our objective is to demonstrate a device, which naturally searches for a selected path out of many possible. Such a device would find a practical application for solving a variety of NP problems (nondeterministic polynomial time), including the traveling salesman problem and the Königsberg bridge problem.

II. COMBINATORIAL DEVICE BASED ON ACTIVE RING CIRCUIT

The schematics of the active ring circuit are shown in Fig. 1(a). It combines electric and electric parts connected in series. The electric part includes a nonlinear amplifier $G(p)$, a variable phase shifter $\Psi$, and a controllable attenuator $A$. These parts are connected via standard coaxial cables. The magnetic part is a delay line—a waveguide made of YIG. Two microstrip antennas excite and receive spin waves through the waveguides. A detailed description of spin-wave excitation and detection with microantennas can be found elsewhere [8].

The group velocity of spin waves propagating in the waveguide is much slower compared with the velocity of electromagnetic waves of the same frequency propagating in the coaxial cable. It provides a prominent phase shift $\Delta$, which is, in general, frequency-dependent. Hereafter, we refer to the phase shifts accumulated inside the magnetic matrix as internal phase shifts. The phase shift provided by the electric phase shifter $\Psi$ will be referred to as external phase shift. The signal circulating in the ring circuit exhibits a conversion from electromagnetic waves to spin waves and vice versa. The corresponding operator equation describing such a system has the form [13]

$$L^{-1} \left( i \frac{d}{dt} \right) c(t) - G(p) c(t) = 0 \quad (1)$$

where operator $L^{-1}(i(d/dt))$ is a linear operator, which describes the oscillating system with delay, $G(p)$ describes the nonlinear amplifier, the function $c(t)$ describes the complex amplitude of the auto-oscillation at the input, and $p = |c(t)|^2$ is the signal power. In the frequency domain, the operator $L(i \, d/dt)$ can be described by a transfer function $L(\omega)$ that is defined as a Fourier transform of the impulse response function of the oscillating system and can be directly measured experimentally. The energy flow into the system is provided by the amplifier, while the passive oscillating system $L$ determines the auto-oscillation frequency and provides positive damping.

The stable limit cycle of the auto-oscillator for the function $c(t)$ has the following form:

$$c_s(t) = \sqrt{p_s} e^{-i\phi(t)} \quad (2)$$

where $\phi(t) = \omega_s t + \phi_0$, $p_s$ and $\omega_s$ are the stationary free-running auto-oscillation power and frequency, respectively, and $\phi_0$ is an arbitrary initial phase of the auto-oscillation. The gain and phase conditions of the auto-oscillation are the following [13]:

$$\text{abs} \left[ L(\omega_0) G(p_s) \right] \geq 1 \quad (3.1)$$

$$\arg \left[ L(\omega_0) \right] + \arg \left[ G(p_s) \right] = 2\pi l \quad (3.2)$$

where $l = 1, 2, 3, \ldots$ is an integer number. The oscillations start when the gain provided by the amplifier $G(p)$ exceeds the losses in the spin-wave system, and the sum of phases within the electric and spin-wave parts matches the ring resonance condition. To simplify our consideration, we assume $\arg[L(\omega)] = \Delta$, and $\arg[G(p_s)] = \Psi$ and neglect the effect

![Figure 1](image-url)
of conducting cables on the phase shift accumulated by the signal.

The ability to self-adjust to the auto-oscillation frequency is the most appealing property of the active ring circuit. In case condition (3.1) is satisfied, the system is naturally searching for the frequency $\omega_1$ to satisfy condition (3.2). This property can be utilized for searching for a resonant part out of many possible. The passive part of the active ring circuit [i.e., the delay line in Fig. 1(a)] can be split on several possible paths, where the paths transmit signals in specific frequency ranges and provide different phase shifts. In this case, the circuit will naturally search for the path, which provides the resonant phase shift to meet (3.2). The examples of multipath circuits comprising frequency filters and delay lines are described in [12].

In Fig. 1(b), a modified active ring circuit is schematically shown with three YIG waveguides connected in parallel. These waveguides have the same material structure and geometry but differ in the direction of the bias magnetic field. Spin-wave dispersion depends on the strength and the direction of the bias magnetic field [14]. For instance, spin waves propagating perpendicular to the external magnetic field, i.e., magnetostatic surface spin waves (MSSW), spin waves propagating parallel to the direction of the external field, i.e., backward volume magneto-static spin waves (BVMSW), and spin wave propagating in a waveguide magnetized normally to its surface, i.e., forward volume magnetostatic spin waves (FVMSW), possess significantly different dispersion. The relation between the frequency and the vector is the following [15]:

$$f_{\text{MSSW}} = \sqrt{\left(\frac{fH + fM}{2}\right)^2 - \frac{fM}{2}} \exp(-2k d_0)$$

$$f_{\text{BVMSW}} = \sqrt{fH \left(\frac{fH + fM}{2} \left(1 - \exp\left(-k d_0\right)\right)\right)}$$

$$f_{\text{FVMSW}} = \sqrt{fH \left(\frac{fH + fM}{2} \left(1 - \exp\left(-k d_0\right)\right)\right)}$$

where $fH = \gamma H_0$, $fM = 4\pi M_0$, and $\gamma = 2.8 \text{ MHz Oe}^{-1}$ is the electron gyromagnetic ratio. $k$ is the wavenumber, and $d_0$ is the film thickness. The difference in the dispersion manifests itself not only in the different phase shifts accumulated for the same propagation length but also in the frequency interval for spin-wave propagation. In Fig. 2, the results of numerical simulations for the dispersion of all three types of spin waves are shown. The numerical modeling is accomplished for YIG waveguide with $d_0 = 0.5 \mu m$, $4\pi M_0 = 1750 \text{ Oe}$, and $H_0 = 1845 \text{ Oe}$. In Fig. 2(a), the dispersion relation for MSSW, BVMSW, and FVMSW is shown. One can see that MSSW and BVMSW intersect only for $k d_0 = 0$. It implies two different frequency regions for signal propagation. In Fig. 2(b), the group velocity for MSSW, BVMSW, and FVMSW is shown. MSSW and FVMSW possess positive group velocity, while BVMSW possesses negative group velocity. YIG waveguides of the same length and geometry may provide significantly different phase shifts to the propagating spin waves. The unique properties of spin-wave dispersion in YIG waveguides make it possible to exploit YIG waveguides as frequency filters and delay lines at the same time.

III. SPIN-WAVE REDIRECTION IN MULTIPORT ACTIVE RING CIRCUIT

Here, we report experimental data on the spin-wave redirection in a multiport structure where signal changes its propagation path depending on the position of the external phase shifter $\Psi$. The schematics of the experimental setup are shown in Fig. 3(a). The electric part consists of an amplifier and a phase shifter. The electric part is connected to a multipport passive path, which consists of a substrate with
microantennas covered by the 6-mm × 18-mm YIG film of thickness 21 µm and a saturation magnetization of 1750 G. There are six microantennas made on PCB, which serve as input–output ports. The photograph of the substrate is shown in Fig. 3(b). The antennas are marked as 1, 2, 3, . . . , 6. Antenna #1 is the input port, while the other five antennas are the output ports. An external magnetic field of 270 Oe was applied in the YIG-film plane, as it is shown in Fig. 3(b).

At such a direction of the bias magnetic field, spin waves propagating from antenna 1 to antenna 2 are close to MSSW. The antennas are connected to the electric part through the system of splitters and combiners. It is possible to measure output power at each of the five outputs. The aim of the experiment is to demonstrate signal redistribution between the output ports (i.e., five possible routes) depending on the position of the electric phase shifter $\Psi$.

In Fig. 3(c), an example of signal distribution between the five output ports for external phase $\Psi = 0 \pi$ is shown. The green circle depicts the output power larger than $-45$ dBm. The yellow circles depict the output ports with the power in the range from $-45$ to $-56$ dBm. The red circles depict the outputs within minimum power below $-56$ dBm.

Any change in the external electric phase shifter makes the system to search for the resonant frequency that meets phase condition (3.2). In turn, the change in the frequency may result in signal redirection. In Fig. 4(a), there are shown experimental data illustrating the change in the power distribution between the output ports for different positions of the phase shifter. The horizontal axis corresponds to the position of the phase shifter. The vertical axis corresponds to the output power. There are five curves of different colors, which correspond to different outputs. One can see that the most of the power comes through port #3, while the least of power comes through port #2 for external phase $\Psi = 0 \pi$. The change of the phase to $\Psi = 0.25 \pi$ redirects most of the energy flow to port #4. The further increase of the phase to $\Psi = 1.5 \pi$ makes the most of the signal come through port #2. It should be noted that the phase change is accompanied with a slight change in the device attenuation. It explains the difference for the power distribution for $\Psi = 0 \pi$ and $\Psi = 2 \pi$.

IV. DISCUSSION

There are several observations we would like to outline based on the obtained experimental data.

1) The experimental data shown in Fig. 4 were obtained on the multiport structure with uniform in-plane bias magnetic field. It is far from the ideal situation shown in Fig. 1(b), where each waveguide supports a different type of spin waves. Nevertheless, the experimental data demonstrate prominent signal redistribution between the output ports, where the difference in power between the red and green marked outputs exceeds 10 dBm.

2) The redirection of the power flow between the paths is controlled by the external phase shifter. It is an interesting physical phenomenon that can be used for magnetic bit addressing and read-out.

3) There may be a variety of practical applications of the active ring circuits with a multipath passive part using different materials and signal delay mechanisms. Spin-wave delay lines are convenient due to the small size and ability to control dispersion by the bias field. For instance, a voltage-controlled spin-wave modulator based on the synthetic multiferroic structure was recently demonstrated [6].

In Fig. 5, a combinatorial device is schematically shown, which can be utilized for data storage memory and data processing. For simplicity, it shows an active ring circuit with just one amplifier and one phase shifter. The magnetic part is a $5 \times 5$ matrix of YIG waveguides. The signal can propagate on horizontal and vertical waveguides connecting the nearest-neighbor sites. Each waveguide serves a delay line and a frequency filter. There are $n$ inputs and $n$ outputs. Each input–output port has a switch to control connectivity to the matrix. Also, each output port has a phase shifter to control condition (3.2). There are two positions for a switch: on and off. There are a number of connection combinations, for example, one input–one output combination, two input–one output port, and so on. There are $2^{2n-2}$ possible combinations.
The overall functional throughput of combinatorial logic devices can be estimated as follows:

$$\text{Functional throughput} = \frac{2^{2n-2} \cdot (n + n)!/(n! \times n!)}{I^2 \cdot n^2 \times l \cdot n^2/v_g}$$  \hspace{1cm} (7)$$

where $I^2 \cdot n^2$ is the size of the multipath matrix, $l$ is the characteristic size of the mesh cell, $l \cdot n^2/v_g$ is the time delay, and $v_g$ is the spin-wave group velocity. Regardless of the size of the delay line and signal propagation speed, the functional throughput of the combinatorial logic devices increases proportionally to $n$ factorial. Potentially, combinatorial logic devices may compete with quantum computers in functional throughput. The traveling salesman person and the Königsberg bridge problems are NP-hard problems to be solved with the help of combinatorial logic devices. The examples of finding a route through selected points on the mesh and finding the shortest route are described in [12].

There are certain physical restrictions on the number of possible paths, which can be recognized. For instance, the number of distinct phases as well as distinct amplitude levels per output is restricted by the accuracy of the phase shifters and attenuators. Also, YIG waveguides have a limited frequency interval for spin-wave propagation, which implies another technical challenge for engineering magnonic matrix. These and other questions deserve a special consideration. This work is aimed to describe YIG-based combinatorial logic devices and outline their most appealing properties.

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