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Magnon phase discriminator of microwave oscillations

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Received July 30, 2024
Revised October 7, 2024
Accepted November 8, 2024

A model of the phase discriminator of the microwave oscillations based on the interference of spin waves in a ferromagnetic film is investigated. The excitation of spin waves in the film is carried out by two microstrip antennas, and the total oscillation due to the inverse spin Hall effect occurred on a platinum bus located between them. An equivalent electrical circuit of a phase discriminator is presented and investigated, and a discriminatory characteristic is obtained as a function of the phase difference of the input oscillations and the ratio of their amplitudes. The micromagnetic simulation of the transformation of spin waves propagating in a ferromagnetic film into an output DC voltage showed good agreement with the dependence obtained theoretically.

Keywords: spin wave, inverse spin Hall effect, phase discriminator, ferromagnetic film.

DOI: 10.61011/TPL.2025.03.60719.20076

Spintronics is one of the promising fields of science and technology, which can be applied for further development of microwave electronics components. It studies the physical effects resulting from the interaction of individual electron spins as well as from-spin-polarized currents flowing in thin magnetic and semiconductor films and heterostructures [1]. Spintronics also includes the application of these effects to micro- and nanoscale information processing devices [2]. Magnonics is a research area in spintronics that studies the process of information transfer in electronic devices, and its carriers are quanta of spin waves — magnons [3]. Therefore, the problems of magnon generation, transport, conversion, and detection are becoming relevant. Various diagrams of detectors [4,5], delay lines [6], neuromorphic calculators [7], etc. have been proposed. The phases of spin-wave oscillations can contain information, and thus it is necessary to be able to compare these phases. One example of computational devices operating according to the principles of information encoding in the wave phase is, for example, a phase discriminator [8]. The idea of constructing a phase discriminator (or phase comparator) was proposed in [9] and an example of micromagnetic simulation was given. The phase discriminator is a device whose operation is based on comparing the phases of two input microwave oscillations and converting the resulting phase difference into an output voltage using a detector. [6] discussed an experiment in which the phase discriminator was considered in the form of a ferromagnetic film of yttrium-iron garnet and three conductive antennas placed on top of it. Electrical signals were applied to two of the antennas used to excite and receive spin waves, and at the third, the phase difference of these signals was converted into a constant voltage proportional to the output power. The purpose of this work to investigate the model of a phase discriminator (PD) of microwave oscillations based on the interference of spin waves in a ferromagnetic film to find the dependence of the constant output voltage on the phase difference of the input oscillations. The total oscillation is converted into this voltage by the inverse spin Hall effect (ISHE) in a layer of normal heavy metal.

Let us consider the structure of a PD in the form of a ferromagnetic film and two strip antennas, which are used to excite spin waves (Fig. 1, a). The operation of the PD is based on comparing the phases of two input microwave oscillations and converting them into an output voltage due to ISHE on a layer of platinum [4]. Microwave signals with $P_{1,2}$ powers and $\varphi_{1,2}$ phases are fed to conductive strip antennas. The electric currents flowing along these lines generate alternating magnetic fields. They interact with the ferromagnetic layer, excite magnetic moment precession and spin waves diverging from the antennas, which interfere and induce an induced current at the output antenna located between the input antennas. The possibility of using the voltage thus induced to construct a phase discriminator was analyzed in [5]. Unlike [5], the output antenna is a heavy normal metal bus bar (e.g., platinum), in which an EDS is induced due to ISHE, which has both constant $U_{dc}$and variable U_{ac} components. We will be interested in the discriminator curve (DC) — the dependence of the constant component of the voltage normalized to the maximum value of the voltage at the output antenna on the phase difference of the input signals, i.e., the dependence $U_{dc}(\Delta\varphi)$, where $\Delta\varphi = \varphi_1 - \varphi_2$ — the phase difference of the input oscillations.

The vector of the stationary magnetization direction is directed perpendicular to the direction of spin wave

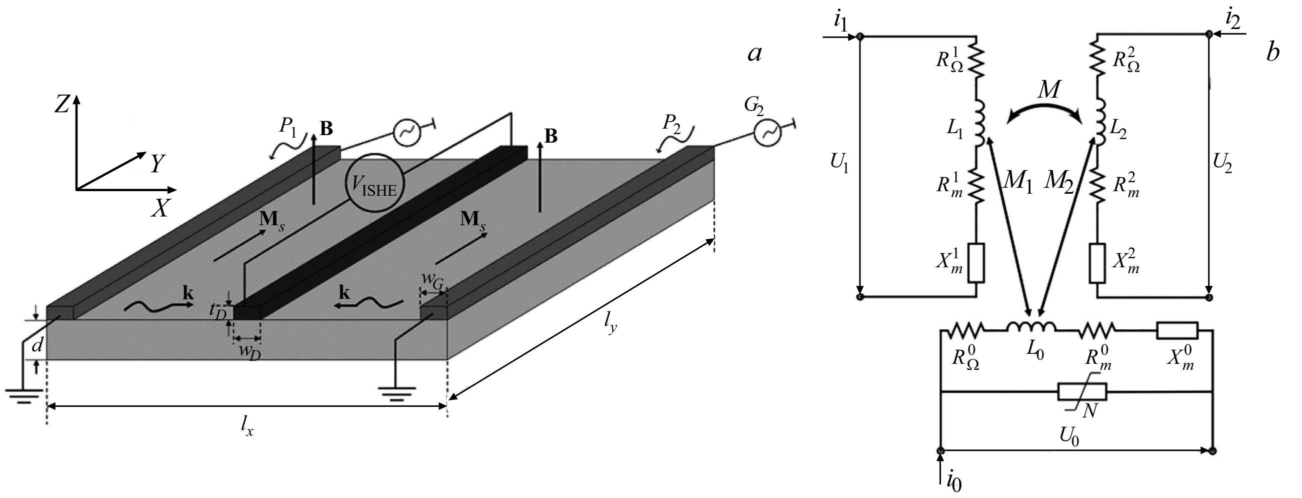

Figure 1. *a* — the schematic representation of the phase detector as a ferromagnetic film and three strip transmission lines; *b* — its electrical equivalent scheme.

propagation in the film plane (surface spin waves are excited) [10]. We will assume that the plane dimensions of the ferromagnetic waveguide are much larger than its thickness: $l_{x,y} \gg d$. In addition, to describe the transmission line under consideration by an equivalent circuit, it is necessary that the antenna length l_y be much smaller than the electromagnetic wavelength λ_{EM} [10]. Note that these conditions are met for the permalloy waveguides used in practice, the longitudinal dimensions of which are given in the [11]. In addition, in magnon waveguide devices, spin waves can be re-reflected at the boundaries and inhomogeneities of the used sample. Such processes can lead to additional phase overlap and distortion of the measured signal. However, we will assume that the waveguide used is long enough so that due to the presence of Hilbert attenuation, the amplitude of waves reflected from the boundaries of the structure in the sample region below the center transmission line will be small.

In [10] an equivalent scheme was proposed for the structure of the type input antenna-film-output antenna in the form of active and reactive loss resistance of the antennas excitation and reception of spin waves, as well as active and reactive resistances that characterize the propagation of spin waves in the ferromagnetic film. Let us supplement this scheme with another one, which will be used for signal acquisition and detection (Fig. $1, b$). Let us consider this equivalent scheme in more detail.

Let us denote the impedance of the output antenna and the two input antennas by Z_0, Z_1 and Z_2 respectively (Fig. $1, b$). We write the resistance$Z_0 = U_0/i_0$ of the output antenna as $Z_0 = R^0_\Omega + V_{ind}/i_0$ [10], where R^0_Ω — ohmic resistance, V_{ind} — voltage induced by EDS. The impedances Z_1 and Z_2 are written similarly to Z_0. From the Maxwell-Faraday equation, we obtain an expression for V_{ind} through the magnetic flux Φ as $V_{ind} = -i\omega\Phi$, where $\Phi = \Phi_0 + \Phi_m$ [10]. Here Φ_0 and Φ_m –fluxes arising from-from the current and from-the precession of the magnetization vector, respectively. L_0, L_1, L_2 — the intrinsic inductances of the output antenna and the two input antennas, respectively (Fig. $1, b$). The resistances X^0_m and R^0_m in the equivalent scheme (Fig. $1, b$) are written as [5]:

$$X^0_m = \frac{\omega\mu_0 d l_y}{8\pi} \int \chi'_{\omega,xx}(k) \left[\frac{1}{k w_D} \sin\left(\frac{k w_D}{2}\right)\right]^2 dk,$$

$$R^0_m = \frac{\omega\mu_0 d l_y}{8\pi} \int \chi''_{\omega,xx}(k) \left[\frac{1}{k w_D} \sin\left(\frac{k w_D}{2}\right)\right]^2 dk, \quad (1)$$

where $\chi_{\omega,xx}(k)$ — component of the complex tensor of the dynamic magnetic susceptibility $\chi_\omega(k) = \chi'_\omega(k) + i\chi''_\omega(k)$. The real part of $\chi'_\omega(k)$ is responsible for the reactance X^0_m, and the imaginary part $\chi''_\omega(k)$ — for the active radiation resistance R^0_m, arising from-due to the propagation of spin waves. We denote the mutual inductances between the detector and the left antenna, between the detector and the right antenna, and between the left and right antennas by M_1, M_2 and M respectively (Fig. $1, b$). M_1 will be written as

$$M_1 = \mu_0 d l_y \int \exp(ikl_x/2)\chi_{\omega,xx}(k)\sin^2(kw_D/2)(1/kw_D)^2 dk.$$

The mutual inductances M_2 and M are written in a similar way. Thus, we obtain the equivalent electrical circuit on lumped elements (Fig. $1, b$).

It was shown in [12] that the electric current density$\mathbf{j} \propto \mathbf{m} \times d\mathbf{m}/dt$, where $\mathbf{m} = \mathbf{M}/M_s$ — is the magnetization vector normalized to the saturation magnetization. Since the unidirectional voltage across the detector is $U_{dc} \propto |\mathbf{j}|$, we have $U_{dc} \propto |\mathbf{m} \times d\mathbf{m}/dt|$. Magnetization $\mathbf{m} \propto \mathbf{A}_0 \exp\big(i(\mathbf{kr} - \Omega t)\big) + \mathbf{m}_0$, where $\mathbf{A}_0$ — the oscillation amplitude of the vector $\mathbf{m}$. Consequently, $U_{dc} \propto |\mathbf{m} \times d\mathbf{m}/dt| \propto \Omega|\mathbf{A}_0|^2$, i.e., the constant component of the voltage U_{dc} is proportional to the power of the

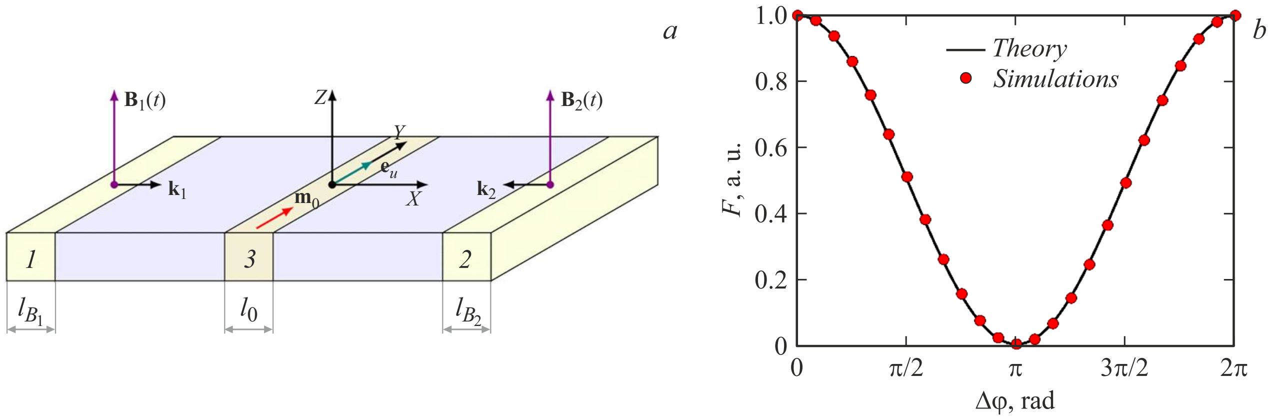

Figure 2. *a* — the diagram of the modeled ferromagnetic film. The ground state is represented by the vector $\mathbf{m}_0$, which is parallel to the anisotropy vector $\mathbf{e}_u$ directed along the light axis. Spin waves with wave vectors $\mathbf{k}_1$, $\mathbf{k}_2$ are excited by $\mathbf{B}_1(t)$, $\mathbf{B}_2(t)$, harmonic magnetic fields, which exist only in the regions *1* (width l_{B_1}) and *2* (width l_{B_2}) respectively. The detection area is labeled by *3* and has a width l_0. *b* — the DC of the phase discriminator. The dots indicate the results of micromagnetic calculations, the solid line — the dependence obtained by formula (3).

magnetostatic wave. In the electrical circuit under consideration, i_0, i_1, i_2 — the strengths of the currents flowing through the spin wave antennas, $U_1(t) = V_1 \sin(\omega t + \varphi_1)$, $U_2(t) = V_2 \sin(\omega t + \varphi_2)$ — the voltages of the input signals, φ_1, φ_2 — their phases and amplitudes. A rectifier (a nonlinear quadratic element) is placed in the part of the circuit that corresponds to the detector, on which the voltage V_{ISHE}will be obtained. We will look for the voltage V_{ISHE} at the output antenna as $V_{\text{ISHE}} = f(V_1, V_2, \varphi_1, \varphi_2)$. From Kirchhoff's equations

$$\begin{cases} U_1 = (pL_1 + Z_1)i_1 - pMi_2 - pM_1 i_3, \\ U_2 = -pMi_1 + (pL_2 + Z_2)i_2 - pM_2 i_3, \\ U_0 = -pM_1 i_1 - pM_2 i_2 + (pL_3 + Z_3)i_3, \end{cases} \tag{2}$$

where $p = d/dt$ — differentiation operator, at $i_0 = 0$, $L_1 = L_2 = L$, $Z_1 = Z_2 = Z$, $M_1 = M_2 = M_0$ we will get that $U_0 = -pM_0[U_1 + U_2]/(pL + Z - pM)$. After certain transformations, we obtain the expression for U_0 in the form of $U_0 = V_0(\Delta\varphi)\sin\big(\omega t + \Psi(\Delta\varphi)\big)$, where

$$V_0(\Delta\varphi) = \frac{\omega M_0 V_1 \sqrt{1 + n^2 + 2n\cos(\Delta\varphi)}}{\sqrt{\big((L - M)\omega\big)^2 + Z^2}}$$

— the voltage amplitude of U_0 and $n = V_2/V_1$. The constant component of the voltage $U_{dc} \propto V_0^2(\Delta\varphi)$, since the current through a nonlinear element is proportional to the square of the voltage across it. Hence, we obtain the DC of the PD in the form of

$$F(\Delta\varphi) = 1 - \frac{4n}{(1+n)^2}\sin^2\left(\frac{\Delta\varphi}{2}\right). \tag{3}$$

The obtained DC is shown in Fig. 2, *b* by a solid line and represents the dependence of the normalized to the maximum value component U_{dc} of the voltage at the output antenna on the phase difference $\Delta\varphi$ of the input signals. Also the normalized constant component of the output voltage depends also on the ratio of the amplitudes n of the input oscillations. The dependence $F(\Delta\varphi)$ has a minimum at $\Delta\varphi = \pi$, which corresponds to the opposite phase of the input oscillations, and maximums at $\Delta\varphi = 0$ and 2π. Thus, based on the obtained dependence, we can conclude that the considered equivalent circuit functionally solves the problem of comparing the phases of input signals. Earlier in [5] the dependence of the normalized amplitude of the U_{ac} component on the phase difference $\Delta\varphi$ of the input oscillations was found for the considered structure. The DC obtained in [5] had a minimum also at$\Delta\varphi = \pi$, and it reached maximum values at $\Delta\varphi = 0$ and 2π.

To verify the theoretically obtained results, micromagnetic simulation was performed in the MUMAX^3 software package. A waveguide of size $40\,\mu\text{m} \times 1\,\mu\text{m} \times 20\,\text{nm}$, divided into $4096 \times 128 \times 4$ computational cells, was simulated (Fig. 2, *a*). The material parameters corresponded to permalloy [9]. The saturation magnetization $M_s = 8 \cdot 10^5$ A/m, the Hilbert damping constant $\alpha = 0.01$, the light axis anisotropy constant $K_u = 1.6 \cdot 10^3\,\text{J/m}^3$, the orth of the light axis direction $\mathbf{e}_u = (0, 1, 0)$, $\mathbf{m}_0$ — steady-state magnetization. To simulate a thin ferromagnetic film, Ament and Rado [13] boundary conditions for the case of free spins were used at the boundaries parallel to the *OXY* plane, and periodic boundary conditions were applied to the other boundaries. To simulate PD, spin waves were excited using $\mathbf{B}_1(t)$, $\mathbf{B}_2(t)$harmonic magnetic fields. In *1* region $l_{B_1} = 5$ nm-wide a magnetic field $\mathbf{B}_1(t) = \big(0, 0, b_0\cos(\Omega t)\big)$, was set, and in *2* region $l_{B_2} = 5$ nm-wide a field $\mathbf{B}_2(t) = \big(0, 0, b_0\cos(\Omega t + \Delta\varphi)\big)$ was set. The amplitude of the magnetic field was chosen to be $b_0 = 25$ mT and the frequency$f = \Omega/2\pi = 4$ GHz. Fields $\mathbf{B}_1(t)$, $\mathbf{B}_2(t)$ excited spin waves with wave vectors $\mathbf{k}_1$, $\mathbf{k}_2$ respectively. Micromagnetic calculations were performed at phase differences of $\Delta\varphi \in [0; 2\pi]$. In the simulations, all three components of the$\mathbf{m} = (m_x, m_y, m_z)$, vector averaged over a detector area of width $l_0 = 5$ nm, were kept every $dt = 1$ ps. The simulation time was 300 ns, which ensured that the results were not affected by transients. Thus, the values of$j_y = [\mathbf{m} \times d\mathbf{m}/dt]\mathbf{e}_u$were obtained. This value is proportional to the rectified voltage U_{dc}. In Fig. 2, b dots represent the results of numerical simulation. The obtained graph of the theoretical dependence of the normalized component U_{dc} of the output voltage on the phase difference and the result of micromagnetic modeling coincide with the graph of such dependence found in [6].

Thus, the principle of operation of a phase discriminator of microwave oscillations based on the interference of spin waves in a ferromagnetic film has been theoretically described in this paper. An equivalent electrical circuit on lumped elements was used to obtain the DC of this detector normalized to the maximum value of the U_{dc} component of the voltage at the output antenna as a function of the phase difference $\Delta\varphi$. It has a minimum at $\Delta\varphi = \pi$, which corresponds to the counter-phase and coincides with the relationship obtained in [6]. Micromagnetic simulation of spin wave propagation in such a film was carried out. The average value of the modulus of the projection of the $\mathbf{m} \times d\mathbf{m}/dt$ vector on the OYaxis was taken as the amplitude of the output signal. The results of numerical and analytical calculations qualitatively coincide, which indicates the correctness of the presented theoretical approach to the description of PD. PD can be used in radio-frequency generators, magnon devices for data processing and image recognition, as well as in magnetic field sensors.

Funding

This study was financially supported by the Ministry of Science and Higher Education of the Russian Federation (Agreement № 075-15-2024-538).

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by J.Savelyeva