Discrete spintronics devices for recording electromagnetic radiation

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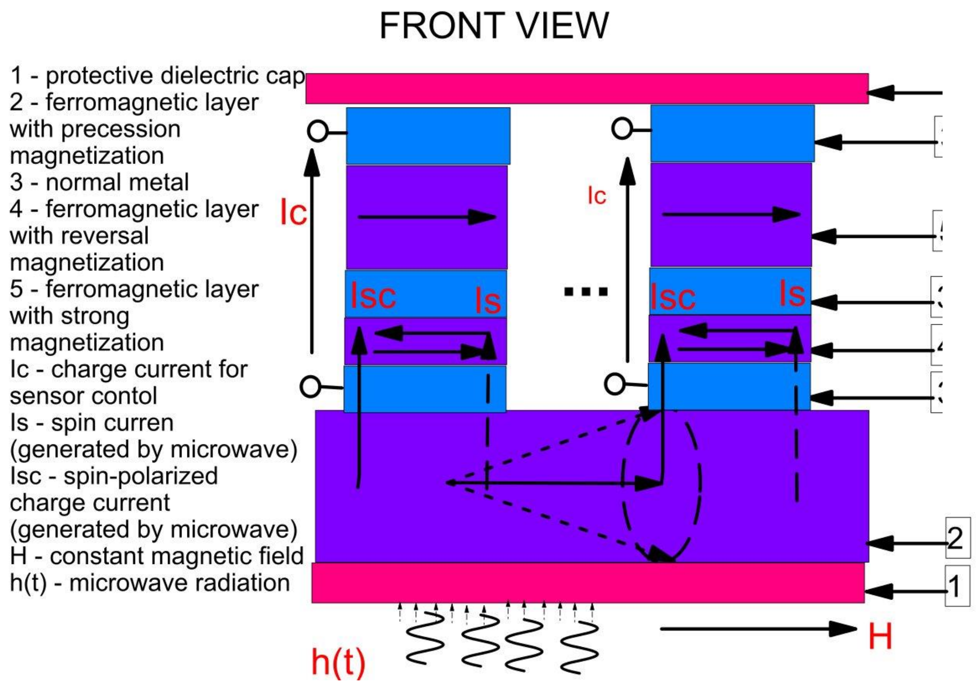

Fig. 1a

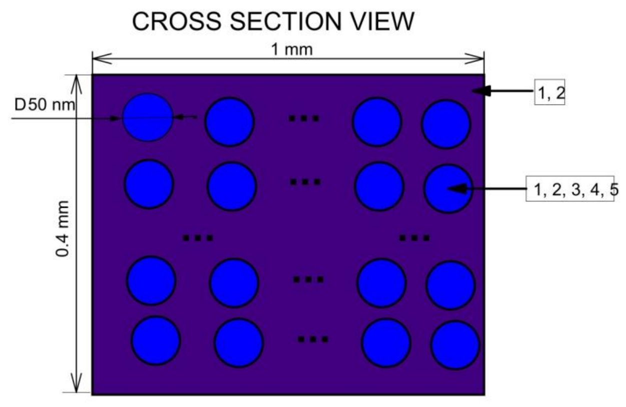

Fig. 1b

INTRODUCTION

Research of Ukrainian scientists in analogous field: **microwave resonance on superconducting high-temperature films** (1986, KNU, G.A. Melkov); creation of surface resonators of electromagnetic waves and combined devices formed by magnetic and superconducting films **[1]**. **Our design** is based on **a system of parallel ferromagnetic nanowires**, on which an external electromagnetic wave falls and excites a **spin current** in the nanowires (**Fig.1, [2]**). Our model is based on the theory of perturbations of a system with two states (spin-up and spin-down) in the approximation of slow waves or **rotating wave approximation (RWA) [3]**.

METHODS

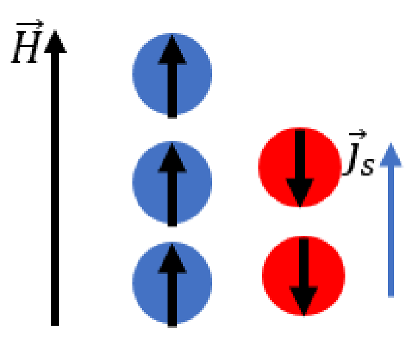

Fig. 2a

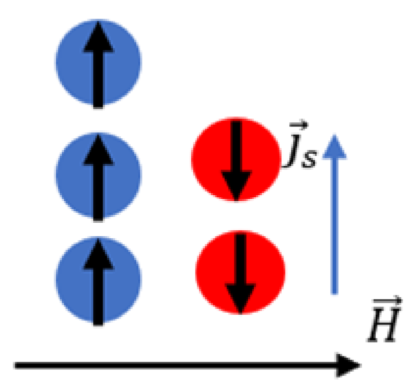

Fig. 2b

The essence of this approximation is that **two spin waves (or spin current) with oppositely directed vectors** can arise in nanowires due to excitation by an **external alternative magnetic field**. We can determine the frequency of emerging waves or oscillations of spin magnetization in nanowires within the framework of **RWA**. The **energy states of the system** are the energy difference of **electrons in the conduction band with the "spin-up" and "spin-down" states in an external constant magnetic field (Fig. 2)**. The possibility of applying this theory is due, in our opinion, to the symmetrical effect of an external disturbance (high-frequency electromagnetic field). This model can be used for both **parallel (Fig. 2a)** and **perpendicular (Fig. 2b)** geometry of the device.

1. Disturbance of the system:

$$V(t) = \gamma e^{i\omega t}|s\uparrow><s\downarrow| + \gamma e^{-i\omega t}|s\downarrow><s\uparrow|,\ \gamma = \frac{1}{2}\mu_B \mu \mu_0 h$$

where $|\boldsymbol{k}>$ and $|-\boldsymbol{k}>$ are ket-vectors of electrons in free band, with spin-up and spin-down spin-orientation;

$\boldsymbol{\gamma}$ is a amplitude value of the energy of interaction of spin and radio-frequency field:

$\boldsymbol{h}$ and $\boldsymbol{\omega}$ are the amplitude and frequency of the magnetic field of the radio-frequency field;

$\boldsymbol{\mu_B} = 9.27 \times 10^{-24}\, J/T$ (**Bohr magneton**); $\mu_0 = 4\pi \times 10^{-7}\ H/m$ (**magnetic constant**);

$\boldsymbol{\mu}$ is magnetic permeability of ferromagnets ($10^2 \div 10^5$).

2. Rotating wave approximation (slow wave):

$$V(t) = \frac{1}{2}\gamma e^{i\omega t} \cdot \left(|s\uparrow><s\downarrow| + e^{-i2\omega t}|s\downarrow><s\uparrow|\right) + \frac{1}{2}\gamma e^{-i\omega t} \cdot \left(e^{i2\omega t}|s\uparrow><s\downarrow| + |s\downarrow><s\uparrow|\right)$$

$$V(t) \approx \frac{1}{2}\gamma e^{i\omega t} \cdot |s\uparrow><s\downarrow| + \frac{1}{2}\gamma e^{-i\omega t} \cdot |s\downarrow><s\uparrow|$$

Hamiltonian system (without loses of energy): $i\hbar \cdot \begin{pmatrix}\dot{c}_1 \\ \dot{c}_2\end{pmatrix} = \begin{pmatrix} 0 & \frac{1}{2}\gamma e^{i\omega t} \\ \frac{1}{2}\gamma e^{-i\omega t} & \Delta E \end{pmatrix} \times \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$

$c_1(t)$ and $c_1(t)$ wave functions of $|\boldsymbol{k}>$ and $|-\boldsymbol{k}>$ states of electrons in free band.

Energy difference of spin-up and spin-down states: $\Delta E = \frac{1}{2}\mu_B B - \left(-\frac{1}{2}\mu_B B\right) = \mu_B \mu \mu_0 H$

Resonant frequency: $\omega_r = \Delta E/\hbar$

Initial conditions (polarization of electrons in free band): $|c_1(0)|^2 = \eta;\ |c_2(0)|^2 = 1 - \eta;$ $0 < \eta < 1.$

REZULTS

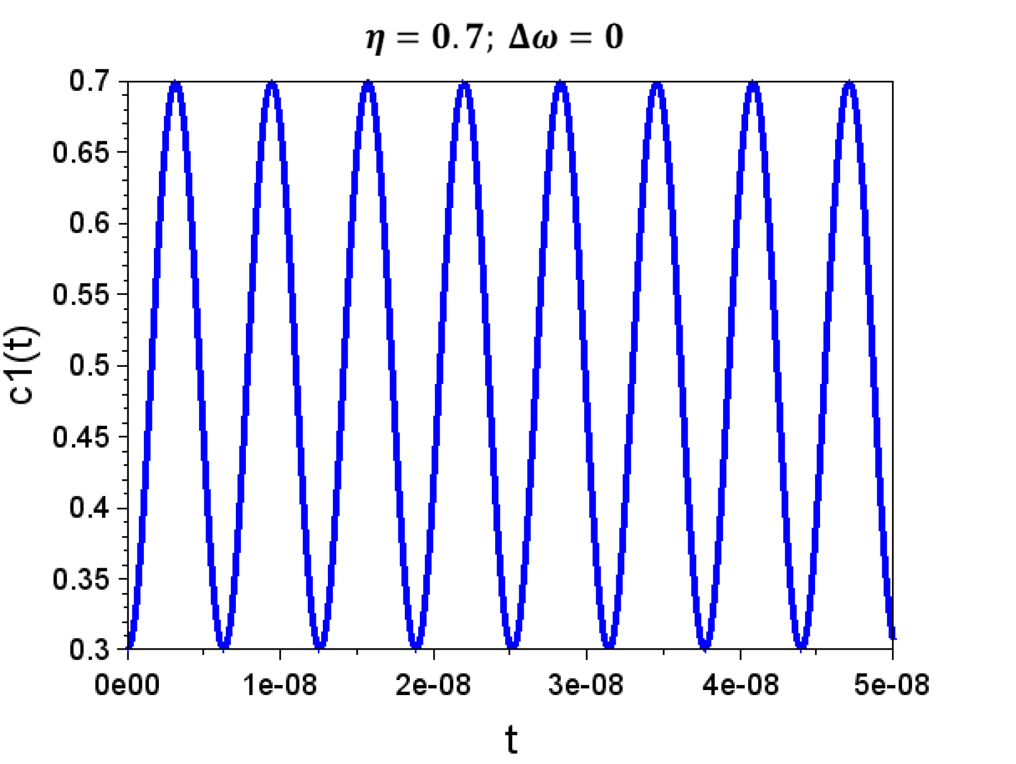

Fig. 3a

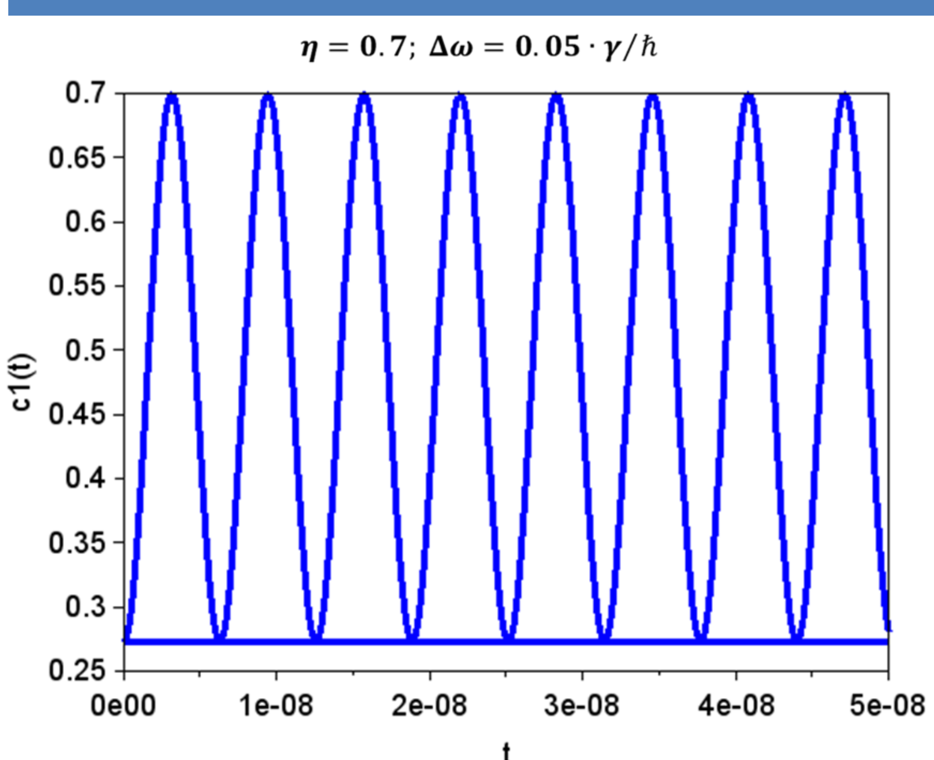

Fig. 3b

3. Rabi's oscillations (near resonant frequency $(\Delta\omega)^2 = (\omega - \omega_r)^2 \ll (\gamma/\hbar)^2$):

$$c_1(t) = e^{\frac{i\cdot\Delta\omega}{2}t} \cdot \left[C_1 \cdot e^{\frac{i\gamma/\hbar}{2}t} + C_2 \cdot e^{-\frac{i\gamma/\hbar}{2}t}\right] \approx C_1 \cdot e^{\frac{i\gamma/\hbar}{2}t} + C_2 \cdot e^{-\frac{i\gamma/\hbar}{2}t}; |c_2(t)|^2 = 1 - |c_1(t)|^2$$

$$C_1 = \frac{(\gamma/\hbar)\cdot\sqrt{1-\eta} - \left(\Delta\omega - \sqrt{(\Delta\omega)^2 + (\gamma/\hbar)^2}\right)\cdot\sqrt{\eta}}{2\sqrt{(\Delta\omega)^2 + (\gamma/\hbar)^2}} \approx \frac{\sqrt{1-\eta}+\sqrt{\eta}}{2}$$

$$C_2 = \frac{\left(\Delta\omega + \sqrt{(\Delta\omega)^2 + (\gamma/\hbar)^2}\right)\cdot\sqrt{\eta} - (\gamma/\hbar)\cdot\sqrt{1-\eta}}{2\sqrt{(\Delta\omega)^2 + (\gamma/\hbar)^2}} \approx \frac{\sqrt{\eta}-\sqrt{1-\eta}}{2}$$

First-order approximation ($\frac{\Delta\omega}{\gamma/\hbar} \approx 0$):

$$|c_1(t)|^2 \approx \left[\sqrt{\eta}\cdot\cos\left(\frac{\gamma/\hbar}{2}t\right)\right]^2 + \left[\sqrt{1-\eta}\cdot\sin\left(\frac{\gamma/\hbar}{2}t\right)\right]^2 = \frac{1}{2} - \left(\eta - \frac{1}{2}\right)\cdot\cos\left(\frac{\gamma/\hbar}{2}t\right).$$

$$|c_2(t)|^2 = 1 - |c_1(t)|^2 \approx \frac{1}{2} + \left(\eta - \frac{1}{2}\right)\cdot\cos\left(\frac{\gamma/\hbar}{2}t\right).$$

Second-order approximation ($\frac{\Delta\omega}{\gamma/\hbar} \approx 0;\ \left(\frac{\Delta\omega}{\gamma/\hbar}\right)^2 \approx 0$):

$$|c_1(t)|^2 \approx \frac{1}{2}\left(1 - \sqrt{1-\eta}\cdot\frac{\Delta\omega}{\gamma/\hbar}\right) - \left(\eta - \frac{1}{2} + \sqrt{1-\eta}\cdot\frac{\Delta\omega}{\gamma/\hbar}\right)\cdot\cos\left(\frac{\gamma/\hbar}{2}t\right).$$

$$|c_2(t)|^2 = \frac{1}{2}\left(1 + \sqrt{1-\eta}\cdot\frac{\Delta\omega}{\gamma/\hbar}\right) + \left(\eta - \frac{1}{2} + \sqrt{1-\eta}\cdot\frac{\Delta\omega}{\gamma/\hbar}\right)\cdot\cos\left(\frac{\gamma/\hbar}{2}t\right).$$

CONCLUSIONS

A model of the interaction of a system of nanowires placed in a constant external magnetic field with an external radio frequency field is considered. The model is based on a quantum approach and uses perturbation theory to determine Rabi oscillations in the slow wave approximation. The results of the model are compared with models of electromagnetic field detection systems containing high-temperature superconducting structures. Thus, within the framework of this model, the phase and amplitude relations for spin waves oscillating in antiphase are derived. These waves lead to fluctuations in the polarization of the ferromagnetic nanowires in which they occur.

REFERENCES

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