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Resonator-Like Antenna for Parametric Excitation of Ultra-Short Spin Waves

In novel, beyond Von Neumann, computational approaches the use of *magnons* (or quanta of spin waves) is particularly promising due to the small intrinsic energies of individual magnons (μeV), the possibility of using phase, in addition to magnitude, as a state variable, and the possibility to control the magnon dispersion properties in a magnetic sample by varying the direction and magnitude of the bias magnetic field [1].

However, the use of magnons in advanced and neuromorphic computing is severely limited by the existing linear methods of magnon excitation, which are based on current-driven inductive transducers which have poor energy efficiency due to Ohmic losses, and are unable to effectively excite ultra-short exchange-dominated magnons. Here we propose to use a resonator-like energy-efficient gate, based on the effect of voltage-controlled magnetic anisotropy (VCMA) [2], as a new type of antenna for parametric excitation and reception of exchange-dominated magnons of a submicron wavelength, having a well-defined phase. When a pumping voltage *V* of a microwave frequency ω_p is applied to a resonator-like VCMA gate, the parametric excitation of two short-wavelength counter-propagating half-pumping-frequency magnons ω_k and ω_{-k} will occur:

$$\omega_p = \omega_k + \omega_{-k},\ k_p \sim 0 = k + (-k)\,. \quad (1)$$

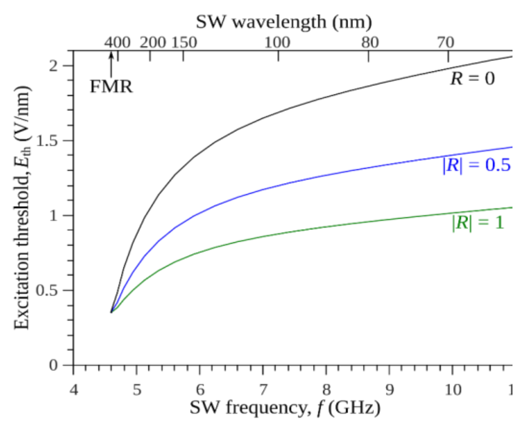

Figure 1. Calculated threshold (electric field) of parametric excitation of spin waves in a VCMA gate as a function of the spin wave wavelength (top axis) and frequency (bottom axis) for different reflection coefficients R at the gate boundaries.

The magnetic anisotropy under the gate will be changed, causing partial reflections of the excited magnons at the both gate boundaries. The excited magnons, then, will have a well-defined phase, that is determined by the phase of the pumping voltage and by the reflection properties of the VCMA resonator. The wavenumber of the excited magnons could be large, and unrelated to the gate size, as it is determined only by the pumping frequency, and the magnon dispersion law $\omega(k)$. The same resonator-like VCMA gate can also act as a receiver of propagating short-wavelength magnons that will create a standing wave under the gate with double the magnon frequency. This standing wave of the frequency ω_p will be detected using a parametric confluence process opposite to the parametric splitting process (1) used for the excitation of magnons at the input VCMA gate. Our calculations show that the reflection of the excited magnons at the gate boundaries reduces the excitation threshold up to two times (in the case of full reflection $|R| = 1$). The calculated excitation threshold for the VCMA gate is presented in Fig. 1. In our calculations we used geometric parameters that are typical for VCMA experiment made on Fe/MgO heterostructures (see e.g. [2, 3]: thickness of the Fe waveguide $t_{\mathrm{FM}} = 1\ \mathrm{nm}$, thickness of dielectric layer $t_{\mathrm{MgO}} = 0.5\ \mathrm{nm}$, waveguide width $w = 50\ \mathrm{nm}$, and the length of the pumping gate $L_g = 1\ \mu\mathrm{m}$. Our preliminary numerical calculation performed for the simplified model of a voltage-biased VCMA gate (see Fig. 1) have demonstrated that the proposed method of parametric excitation and reception of ultra-short-wavelength magnons is realistic, and can be implemented in experiment to generate phase-modulated magnon signals of sub-micron wavelength with high energy efficiency in the GHz and sub-THz frequency ranges.

[1] A. Mahmoud, F. Ciubotaru, F. Vanderveken, A. V. Chumak, S. Hamdioui, C. Adelmann, and S. Cotofana, "Introduction to spin wave computing," *Journal of Applied Physics,* vol. 128, no. 16, p. 161101, 2020.

[2] P. Khalili Amiri and K. L. Wang, "Voltage-controlled magnetic anisotropy in spintronic devices," *SPIN,* vol. 02, no. 03, p. 1240002, 2012.

[3] R. Tomasello, R. Verba, V. Lopez-Dominguez, F. Garesci, M. Carpentieri, M. Di Ventra, P. Khalili Amiri, and G. Finocchio, "Antiferromagnetic Parametric Resonance Driven by Voltage-Controlled Magnetic Anisotropy," *Physical Review Applied,* vol. 17, no. 3, p. 034004, 2022.

Short Bio

Andrei Slavin received PhD degree in Physics in 1977 from the St. Petersburg Technical University, St. Petersburg, Russia.

Dr. Slavin developed a state-of-the-art theory of spin-torque oscillators, which has numerous applications in the theory of current-driven magnetization dynamics in magnetic nanostructures. His current research support includes multiple grants from the U.S. Army, DARPA, SRC and the National Science Foundation. This research involves international collaborations with leading scientists in many countries, including Germany, Ukraine, France, Italy, and the United States. Dr. Slavin is a frequently invited speaker at international conferences on magnetism around the world.

Andrei Slavin is Fellow of the American Physical Society, Fellow of the IEEE, and Distinguished Professor and Chair of the Physics Department at the Oakland University, Rochester, Michigan, USA.