AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **117**, 17E101 (2015); doi: 10.1063/1.4906209
View online: http://dx.doi.org/10.1063/1.4906209
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/117/17?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS 117, 17E101 (2015)

Hybrid yttrium iron garnet-ferromagnet structures for spin-wave devices

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(Presented 6 November 2014; received 21 September 2014; accepted 1 October 2014; published online 21 January 2015)

We study coupled ferromagnetic layers, which could facilitate low loss, sub 100 nm wavelength spin-wave propagation and manipulation. One of the layers is a low-loss garnet film (such as yttrium iron garnet (YIG)) that enables long-distance, coherent spin-wave propagation. The other layer is made of metal-based (Permalloy, Co, and CoFe) magnetoelectronic structures that can be used to generate, manipulate, and detect the spin waves. Using micromagnetic simulations, we analyze the interactions between the spin waves in the YIG and the metallic nanomagnet structures and demonstrate the components of a scalable spin-wave based signal processing device. We argue that such hybrid-metallic ferromagnet structures can be the basis of potentially high-performance, ultra low-power computing devices. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4906209]

I. INTRODUCTION

A holy grail of nanoelectronic research is to develop devices and circuit technologies that could surpass CMOS technology at least in certain figures of merit. Magnetoelectronic devices are top contenders for the title of such "beyond Moore" technologies. Spin can enrich the functionality of electrical circuits,[1] but magnetization state,[2,3] or the spin-wave amplitude and phase[4–7] may entirely substitute electrical charge as information carrier.

A unique strength of spin-wave based computing paradigms is that they allow the realization of wave-based, non-Boolean computing algorithms. For example, by using wave interference as the elementary operation one can design massively parallel signal processing algorithms and essentially re-invent optical computing[8] on the nanoscale.[9–11] Spin-waves can be used for on-chip communication,[4] and if needed, Boolean logic operations can be performed as well.[12] The small wavelength of spin-waves (potentially $\lambda < 10\,\text{nm}$) and their high frequency (potentially in the several 100 GHz range) enables fast, high-integration devices and also CMOS-compatibility.

Spintronic devices (such as spin-torque oscillators (STOs) and magnetoresistive structures) are made from amorphous, metallic ferromagnets (Permalloy, CoFe, etc.) that are conductors and can be deposited and patterned with straightforward technologies. It is also experimentally demonstrated that short-wavelength spin waves can be generated in such ferromagnetic thin films,[13] which opens the way for spin-wave based computing devices. Due to the large damping constant of metallic ferromagnets, the typical spin wave decay length is on the order of $2\,\mu\text{m}$,[13] so only very small-scale spin-wave devices could be built.[14] Strong damping also comes with high thermal noise, which degrades signal integrity. Spin-wave based computing blocks must be scalable beyond a few micrometer sizes, since magneto-electrical interfaces and/or spin-wave amplifiers come with a large energy and area footprint.

Unlike metallic ferromagnets, Yttrium Iron Garnet (YIG) is an excellent medium for spin-wave propagation, having one to three orders of magnitude smaller magnetic damping than Permalloy.[15] But YIG is an insulator, it is challenging to deposit high-quality YIG thin films and also challenging to pattern YIG on the nanoscale. Spin-waves in YIG are usually excited by RF antennas and it is very difficult to excite short-wavelength, exchange-dominated waves this way.[27] Magnetostatic waves can be straightforwardly excited but they typically have several micrometers or longer wavelength,[16] making them impractical for microlectronics applications. In fact, most experimental studies on YIG-based devices deal with long-wavelength magnetostatic waves in YIG, and it is often taken for granted that the devices will be scalable all the way down to the regime of exchange waves.[7]

It remains as a fundamental challenge for spin wave based devices that no material is known that would simultaneously allow low-damping propagation of short-wavelength spin waves and electrical generation/manipulation/detection of spin waves in nanoscale magnetic structures. Our paper addresses this problem by a magnetic bi-layer, which is built from permalloy nanostructures grown on top of a low-damping YIG film.

The operation of the proposed structure relies on exchange and dipolar interactions between a continuous YIG film and patterned Permalloy-based devices and layers on top of this film. Spin waves created in the Permalloy layer can be injected in the YIG film and the local stray field from nanomagnets on top of the YIG film can alter the propagation of the spin waves inside the YIG film. The YIG layer needs not to be patterned and is expected to remain a low damping propagation medium.

Similar bi-layers were studied for applications in bubble memories[17] and very recently, spin-wave propagation in

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these bilayers were characterized as well.[18,19] To our knowledge, no application areas for such bi-layers (apart from the now obsolete bubble memories) were proposed.

II. MICROMAGNETIC MODEL OF THE PERMALLOY-YIG SYSTEM

We used the established OOMMF[20] code and determined the behavior of spin waves by postprocessing time-domain results.

For Permalloy, we used values for saturation magnetization $M_s^{Py} = 8.6 \times 10^5$ A/m, exchange stiffness $A_{exch}^{Py} = 1.3 \times 10^{-11}$ J/m, and damping constant $\alpha^{Py} = 0.008$. For YIG, we used saturation magnetization $M_s^{YIG} = 1.6 \times 10^5$ A/m, exchange constant $A_{exch}^{YIG} = 4 \times 10^{-12}$ J/m, and approximated the damping constant $\alpha^{YIG} = 0.001$.[21] We assumed K = 0 crystalline anisotropy for both materials.[21]

One of the most important parameters of our simulations is the exchange parameter between the YIG and the Permalloy layer, which is characterized the strength of the ferromagnetic interaction between the metal layers. Neglecting higher-order interaction terms, the ferromagnetic interaction can be described either by a J bilinear exchange constant or an $A_{\text{interface}}$ interface exchange stiffness. There are surprisingly few experimental works characterizing this interaction. Chun and Krishnan[22] studied a Fe/YIG system, finding a high $A_{\text{interface}}$, typical of coupled metallic ferromagnetic layers. Youssef *et al.*[18] measured a similar system using FMR techniques,[23,24] but the resulting exchange constant is much lower and more similar to values found in exchange-coupled layers.

In our simulations, we used the $J = 1.8 \times 10^{-4}$ J/m^2 value of Ref. 18 as the lower bound for the interaction and we studied spin-wave behavior for higher interaction strengths as well.

In order to study wave propagation (for the simulations of Secs. III and VI), we created spin waves in the YIG film by a high-frequency spin torque current. This is an artificial way and serves only the purpose to study wave propagation; we study realizable scenarios in Sec. IV. We also used a relatively coarse numerical grid ($\Delta x = \Delta y = \Delta z = 5$ nm), to avoid exceedingly long simulation times.

To set the magnetization direction in the film and keep it from breaking to domains, we applied a $B_{ext} = 0.9$ T external magnetic field in 87° out of plane. For the simulation we define a linearly increasing damping coefficient in a 25 nm wide region around the edges in order to realize absorbing boundary conditions.

III. EXCHANGE-WAVE PROPAGATION IN A COUPLED YIG-PERMALLOY BILAYER

The dispersion relation for exchange-dominated waves is textbook material and for simplified geometries, analytical solutions are available.[16] We numerically determined the $f(k)$ and $H(k)$ functions for our geometry and the results are shown in Figure 1. Note that the frequency ranges (few tens GHz) and the wavelengths ($\lambda < 100$ nm) are both highly compatible with potential micro- and nanoelectronic applications.

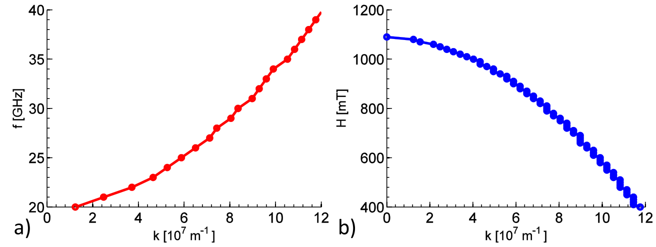

FIG. 1. Dispersion relation in a 5 nm thick YIG film. (a) The frequency–wavenumber relation. (b) The external field–wavenumber relation. Wavelengths ($\lambda = 2\pi/k$) and frequencies are ideal for many nano/microelectronic applications.

If a 5 nm thick Permalloy layer is placed on top of a 5 nm YIG film, then the two layers interact via dipole and exchange interactions. For the studied geometry, assuming the lowest estimate for $A_{\text{interface}}$, exchange interaction is dominant. Fig. 2 shows a pseudocolor plot of the dispersion relation for various $A_{\text{interface}}$ values. The plot was generated by taking the spatial Fourier transformation of the spin-wave amplitude in YIG, so if multiple modes are present, their relative intensity is shown as well.

For small interaction strengths, the dispersion curve shifts to higher frequencies—qualitatively, this is a consequence of the higher effective exchange stiffness that the YIG layer experiences. A low-frequency node appears for higher coupling strengths, which is a propagating exchange wave in Permalloy—we verified this by running simulations for a stand alone Permalloy layer under the same conditions as Figs. 2(a)–2(e) was made and the $f(k)$ curve is almost

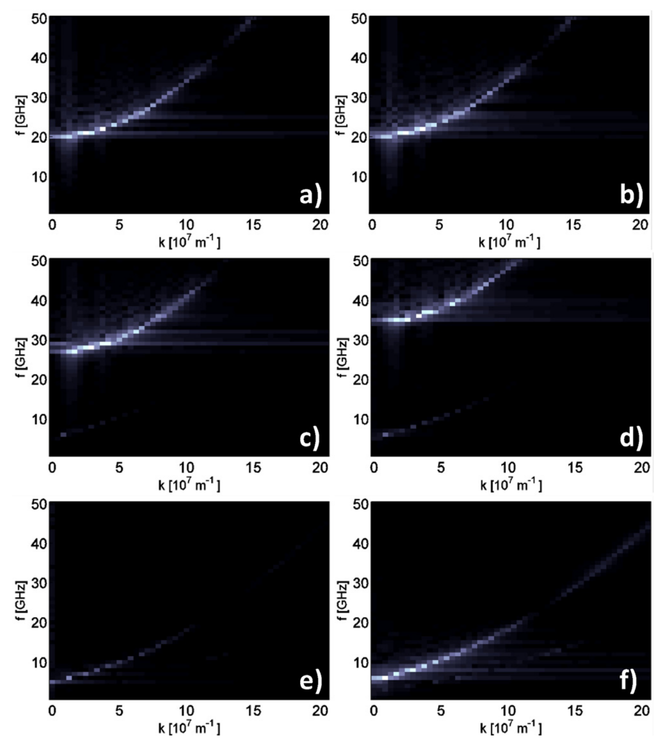

FIG. 2. Numerically calculated dispersion plots for a YIG-Py bilayer. (a) Stand-alone YIG film. (b) $A_{\text{interface}} = 0$ J/m, (c) $A_{\text{interface}} = 0.5 \times 10^{-12}$ J/m, (d) $A_{\text{interface}} = 1 \times 10^{-12}$ J/m, (e) $A_{\text{interface}} = 6 \times 10^{-12}$ J/m, (f) Single Permalloy film. The YIG mode shifts due to the interaction and an additional Permalloy mode appears for stronger couplings.

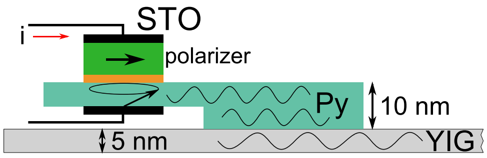

FIG. 3. Sketch of the proposed structure for spin wave injection to YIG. The spin waves generated in the Py layer couple into and propagate in the underlaying YIG film.

identical to the low-frequency mode of Figs. 2(c)–2(e). The Permalloy mode remains weak even for stronger coupling strengths and it appears that the damping of the YIG film is not significantly increased by the Permalloy film on top.

At a given excitation frequency, the wavelength shift caused by the Permalloy overlayer can be interpreted in such a way that the Permalloy overlay changes the effective index of refraction of the YIG film. In analogy to optical devices one may exploit this in order to design lenses,[11] phase shifters, and holograms for on-chip "YIG optical devices."

IV. SPIN-WAVE INJECTION STRUCTURES

Exchange waves in YIG could be created by very small-size antennas[7] or nanoscale inhomogeneities of a YIG film.[25] This is very challenging—and probably a primary reason behind the lack of studies concerning exchange waves in YIG. In ferromagnetic conductors, propagating exchange waves can be straightforwardly created by spin-torque oscillators (STOs).[13] It may be possible to use the exchange coupling mechanism between the YIG layer and the Permalloy to inject short-wavelength spin-waves into YIG. In order to study the feasibility of such a device, we performed simulations on a spin-torque structure, which is exchange-coupled to a YIG layer. A sketch of a highly idealized arrangement is shown in Fig. 3.

Magnetization oscillations are generated in the free layer of the STO and via a short protrusion, they arrive to the underlying YIG film. The simulations (in Fig. 4) show that the spin waves couple into the YIG and propagate there.

We used an AC current to drive the STO, so the free layer frequency is injection locked to this frequency—this way one can arbitrarily define the phase, frequency, and

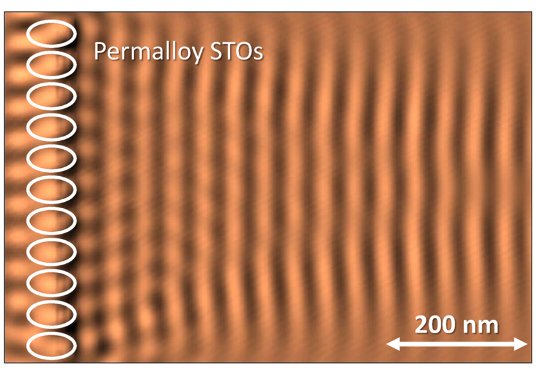

FIG. 4. Waves injected in a YIG film by a line of STOs. The STOs are phase-locked and generate a coherent waveform, which is coupled into the YIG layer.

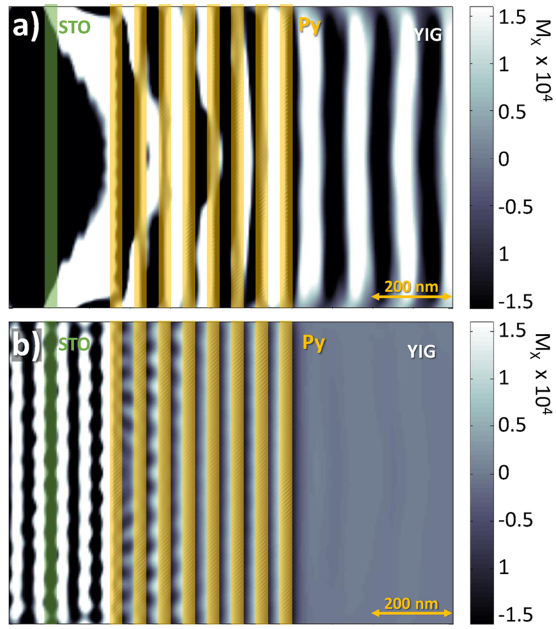

FIG. 5. One-dimensional crystal made out of Py on top of YIG film. (a) f = 24 GHz, (b) f = 38 GHz. The position of the 30 nm spaced Permalloy stripes is denoted by the yellow lines. Different frequencies/wavelength may be completely transmitted or reflected by the crystal.

driving current of the STOs. For simplicity, we neglected the Oersted field coming from the leads of the STO.

The above-shown models are based on an idealized geometry—but they show that it is, in principle, possible to inject spin waves from STO-based sources to YIG via coupling between the two films. The size of the spin-wave generating structure ($d < 100$ nm) matches the wavelength of exchange waves, which may allow high-efficiency spin-wave injection into a single propagating mode.

V. MAGNONIC CRYSTALS FROM BILAYERS

As an example for "spin-wave optics" devices, we show how a magnonic crystal-like structure can be constructed from the proposed bilayers. Magnonic crystals are mostly made from metallic ferromagnets and are widely studied,[26] but their usefulness is severely limited by the high damping of the metallic ferromagnet. Permalloy-YIG bilayer based devices may solve this problem.

The simulation example of Fig. 5 shows spin-wave propagation in a YIG film, with Permalloy stripes on top of it. The Permalloy stripes periodically modulate the index of refraction and act akin to a one-dimensional magnonic crystal. Depending on the spacing of the stripes and the wavelength, this periodic potential may reflect or transmit incoming spin waves. The magntonic crystal is defined without patterning the YIG film, circumventing technological challenges, and increased damping from rough edges.

VI. CONCLUSIONS: TOWARD DEVICES

We have shown proof of principle simulations for Permalloy-YIG bilayer devices. We argued that this device unites the benefits of metal-based magnetoelectronic components and low-damping YIG films and can have potential for spin-wave based signal processing devices.

There are a number of ongoing efforts aiming to incorporate YIG (or similar low damping materials) into spintronic devices-spin Hall effect (SHE) is one promising way to do that.[21] Our work shows a complementary approach, which does not require the use of new physics phenomena; rather, it relies on the integration of known spintronic devices with YIG.

ACKNOWLEDGMENTS

The authors are grateful to George Bourianoff (Intel Corp, Austin, TX) and for Giovanni Carlotti (University of Perugia) for motivating discussions. This work was partially supported by the NSF/SRC grant "Nanoelectronics Beyond 2020" and by a grant from Intel corporation.

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