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Perspective Article

Perspectives of using spin waves for computing and signal processing

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A B S T R A C T

Almost all the world's information is processed and transmitted by either electric currents or photons. Now they may get a serious contender: spin-wave based devices may just perform some information processing tasks in a lot more efficient and practical way. In this article, we give an engineering perspective of the potential of spin-wave-based devices. After reviewing various flavors for spin-wave-based processing devices, we argue that the niche for spin-wave based devices is low-power, compact, high-speed signal processing devices, where most traditional electronics shows poor performance.

1. Introduction: flavors of spin-wave based devices

It is widely acknowledged that Moore's law – the exponential scaling of semiconductor performance in the past few decades – is about to come to an end [1]. The research field for new computing devices is wide open for disruptive ideas. This presents a unique opportunity for studying fundamentally new device concepts – among them devices that use the spin degree of freedom for representing and transmitting information [2]. There are many possible approaches for spin-based processing: one may use single-domain magnetic states and their interactions [3] or electrically-interconnected devices with magnetic layers lying at the heart of their operation. A less straightforward way is to think about a dynamic computing device, one that uses collective excitations of a spin-lattice for information processing. Such devices are the subject of this article.

Spin waves (magnons) are rather different from electromagnetic waves, but small-amplitude spin waves display interference phenomena very similar to photonic interference. It is instructive to draw an analogy between electromagnetic waves and spin waves, as most spin-wave-based information processing devices (magnonic devices) can find their origin in a photonic structure – and proposed magnonic devices face challenges similar to their photonic counterparts [4].

Just as in the case of photonic devices, one may follow two distinct routes toward information processing [5]. One route aims to replicate the functionality of electronic transistors and logic gates and follow the footsteps of highly successful digital electronic circuitry. The advantage of this approach is that there is a clear path toward large and complex computing systems. Boolean circuitry, however, may not be a very good fit to spin-wave based devices and it is not at all clear whether spin-wave based Boolean networks will be competitive with highly optimized, CMOS-based computing devices. Photonic logic devices may give a lesson here: despite numerous benefits, the input / output overhead and their relatively large (wavelength-scale) size makes them impractical as a replacement for CMOS-based circuitry.

Non-Boolean device constructs may allow one to exploit the unique benefits of spin waves, i.e. the computational power of interference pattern formation. This is often referred as 'wave-based computing' or 'holographic computing' and in optics, such computational primitives were widely known under the titles 'Fourier optics' or 'Information optics' [6]. Wave computing does not lend itself easily to general-purpose computing tasks, but provides relatively simple and elegant ways for e.g. doing linear filtering, or calculating Fourier transforms [7]. These are important computing primitives and, for example, in image processing algorithms and in neural networks such simple and repetitive transforms may be responsible for the bulk of the power consumption [8].

An additional application of non-Boolean processing (linear transforms) is that these algorithms are key components in microwave processing algorithms (i.e. in the front-end of radio-

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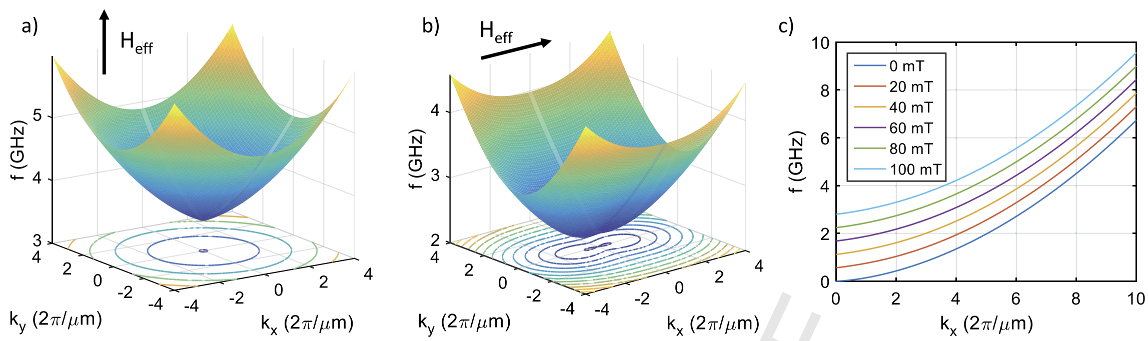

Fig. 1. Dispersion relations for spin-wave propagation in YIG. *a*) Isotropic spin-wave propagation in a perpendicularly magnetized film. *b*) Anisotropic propagation for in-plane SWs. *c*) Magnetic field dependence of the dispersion relation.

frequency and telecommunication devices). In such applications, real-time processing is required in the several ten gigahertz frequency range. There are no low-energy CMOS solutions for these tasks – transistor-based, active circuits consume significant power in order to overcome noise and parasitic effects. We will argue that spin-wave-based devices make intrinsically good high-frequency signal processors. The use of magnetic materials for this purpose is not at all new [9,10], but adding spin-wave interference to the toolbox may open new horizons.

There are a number of excellent review articles focusing on spin-wave logic devices or magnonic crystals – the latter being perhaps the most established area of spin-wave based devices. The readers are referred to [11–14]. The paper of Chumak et al. [5] is a comprehensive review of spin-wave-based, beyond-Moore devices. In this article, we focus on the less-traveled, but, in our opinion, promising route of non-conventional, non-Boolean device structures.

2. Crash course on spin waves

Spin waves (SWs) are wave-like excitations in magnetic materials – the waves propagate by either exchange or dipole interactions between precessing spins. SWs can be understood as particular, wave-type solutions of the time-dependent Landau–Lifshitz–Gilbert equation (LLG) [12]. The LLG equation describes the dynamics of the $\mathbf{M}(\mathbf{r}, t)$ magnetization distribution, and, under some circumstances, the solution can be approximated as $M_a \propto \sin(2\pi f \mathbf{k} t)$, $M_b \propto \cos(2\pi f \mathbf{k} t)$, $M_c = \text{const.}$, where M_a, M_b, M_c are the x, y, z components of the $\mathbf{M}(\mathbf{r}, t)$ magnetization vector, f is the spin-wave frequency and $\mathbf{k}$ is the wave vector. Plane-waves are small perturbations of a uniformly magnetized spin-ensemble. For most practical purposes we are interested in magnetic thin-films.

It is easy to see that depending on the relative orientation of $\mathbf{M}$ and $\mathbf{k}$, there are different possible propagation modes. From the theory point of view, the most straightforward case is $\mathbf{M} \perp \mathbf{k}$, such as in the case of an out-of plane magnetized thin-film – a particular dispersion relation for this case is shown in Fig. 1a. Spin-wave propagation is isotropic in this case. An example of an anisotropic in-plane spin wave propagation is given in Fig. 1b. The curves of Fig. 1 are valid only for thin (thinner than a few-ten nanometers) magnetic films, which films are the most relevant for the device applications discussed here – for thicker films, additional modes may appear.

The dispersion relations show that typical frequencies in the 5–100 GHz range correspond to wavelengths in the ten nanometers – few micrometers range. This perfectly matches the frequency range and size scale where modern electronic circuits operate. Spin-wave wavelengths go all the way down to the nanometer range, so spin-wave-based devices (unlike photonic structures) can be scaled all the way down to the sizes of end-of-the-roadmap semiconductor devices. Also, spin-wave wavelengths at microwave frequencies are about six orders of magnitude shorter then electromagnetic waves – this hints at the possibility of using spin waves for replacing bulky (centimeter-scale) microwave structures.

The high-frequency tail of the dispersion relation in yttrium iron garnet (YIG) reaches the low THz regime, where electronic circuitry is more challenging or impossible to design.

Spin waves propagate by two distinct mechanisms: short-wavelength (typically $\lambda < 100$ nm) SWs by the locally strong exchange interactions and long-wavelength SWs by dipolar interactions. Fortunately, the ways of creating and manipulating these two SW regions can be done by similar methods, but for most practical purposes one tries to operate in the exchange-dominated, short-wavelength regime.

Another benefit of spin waves is illustrated in Fig. 1c, which shows how the dispersion relation can be altered by the application of a magnetic field. The frequency and wavelength can be tuned to the possible application. Also, one may tune $\frac{d\lambda}{df}$ i.e. the frequency sensitivity of the wavelength.

Engineering SW dispersion is extensively researched in the framework of magnonic crystals [12,13].

The propagation length of spin waves for long was considered a problem: due to relatively strong damping and fast decay of the SW amplitude, complex interference patterns were hard to generate in thin-films. Recently, it became possible to reach SW propagation for at least few-hundred wavelength distances [15], which is still short compared to optical waves, but sufficient for many device applications.

Historically, the potential applications of SWs for microwave processing were recognized long ago, and low-loss magnetic materials with engineered spin wave spectrum were used in microwave passive filters, signal-to-noise enhancers and as tunable inductors [10]. In these applications, the magnetic materials were used as a tunable inductive load, but the spatial complexity of SW interference patterns was not exploited. Modern nanotechnologies allow direct access to SW interference patterns, opening up opportunities for new devices.

2.1. Manipulating spin waves

Fig. 1c shows the sensitivity of the dispersion relation to magnetic fields. Changes in the $\mathbf{H}_{\text{eff}}$ effective magnetic field change the dispersion relation, changing the effective index of refraction for the magnetic thin film (and shifting spin-wave phase).

There are a number of possibilities for engineering the magnetic field landscape on the submicrometer size scale. Changing the thickness of the magnetic film changes the effective field and can realize waveguides for spin waves [16]. Another approach relies on breaking the periodicity of a magnonic crystal array [17].

An especially promising idea is to create localized magnetic fields by additional layers of magnetic materials [18,19]. Using Yttrium Iron Garnet (YIG) enables low-loss spin-wave propagation,

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