Perspectives of Using Spin Waves for Computing and Signal Processing

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Abstract

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.

Keywords: Magnonics, spin waves, logic devices, microwave processing

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-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-

65 wave-based devices make intrinsically good high-frequency
signal processors. The use of magnetic materials for this¹²⁰
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
70 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] [12] [13] [14]. The
paper of Chumak et. al. [5] is a comprehensive review of
spin-wave-based, beyond-Moore devices. In this article, we
75 focus on the less-travelled, 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 mag-
netic materials - the waves propagate by either exchange
80 or dipole interactions between precessing spins. SWs can
be understood as particular, wave-type solutions of the
time-dependent Landau-Lifshitz-Gilbert equation (LLG)¹²⁵
[12]. The LLG equation describes the dynamics of the
 $\mathbf{M}(\mathbf{r}, t)$ magnetization distribution, and, under some cir-
cumstances, the solution can be approximated as $M_a \propto$
95 $\sin(2\pi f \mathbf{k} t)$, $M_b \propto \cos(2\pi f \mathbf{k} t)$, $M_c = \text{const.}$, where M_a ,
 M_b , M_c are the x , y , z components of the $\mathbf{M}(\mathbf{r}, t)$ mag-¹³⁰
netization 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
90 purposes we are interested in magnetic thin-films.

It is easy to see that depending on the relative orienta-¹³⁵
tion of $\mathbf{M}$ and $\mathbf{k}$, there are different possible propagation
modes. From the theory point of view, the most straight-
forward case is $\mathbf{M} \perp \mathbf{k}$, such as in the case of an out-of
95 plane magnetized thin-film - a particular dispersion rela-
tion for this case is shown in Fig. 1a. Spin-wave propaga-¹⁴⁰
tion 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
100 few-ten nanometers) magnetic films, which films are the
most relevant for the device applications discussed here -¹⁴⁵
for thicker films, additional modes may appear.

The dispersion relations show that typical frequencies
105 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 mod-
ern 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
110 the way down to the sizes of end-of-the-roadmap semicon-
ductor devices. Also, spin-wave wavelengths at microwave
frequencies are about six orders of magnitude shorter than¹⁵⁵
electromagnetic waves - this hints at the possibility of us-
ing spin waves for replacing bulky (centimeter-scale) mi-
crowave structures.

The high-frequency tail of the dispersion relation in
yttrium iron garnet (YIG) reaches the low THz regime,¹⁶⁰

where electronic circuitry is more challenging or impossible
to design.

Figure 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.

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 oper-
ate 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 wave-
length.

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 mi-
crowave processing were recognized long ago, and low-loss
magnetic materials with engineered spin wave spectrum
were used in microwave passive filters, signal-to-noise en-
hancers and as tunable inductors [10]. In these applica-
tions, the magnetic materials were used as a tunable in-
ductive load, but the spatial complexity of SW interference
patterns was not exploited. Modern nanotechnologies al-
low direct access to SW interference patterns, opening up
opportunities for new devices.

2.1. Manipulating spin waves

Figure 1c shows the sensitivity of the dispersion re-
lation 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, adding metallic nanomagnets on top changes the magnetic field landscape seen by the SWs.

There are more unusual and potentially flexible ways to manipulate spin waves, such as optically [20], or by heat-assisted nanopatterning [21].

Perhaps the most straightforward way to guide SW propagation is patterning the magnetic film. This is straightforward for the case of metallic ferromagnets and it has recently become possible for less fabrication-friendly materials, such as YIG [22].

It is extremely useful if the potential landscape of the magnetic materials can be manipulated in a dynamic, reconfigurable way [23]. Strain control of spin waves [24] could potentially enable reconfigurable steering of spin waves with very low energy.

2.2. Energetics of spin waves

A major motivation for spin-based electronics is addressing the power bottleneck of today's microelectronic devices. For static, spin-based logic devices there are strong reasons to believe that they can dissipate very low power during operation [25]. For SW-based devices, much less research was done. A simple calculation [26] suggests that a relatively complex calculation (a 64-point Fourier transform) can be done with a spin-wave wavefront carrying a mere few-ten electronvolts of energy. As the formation of the interference pattern takes place on the nanosecond time scale, the power efficiency of computing based on spin-wave interference pattern is orders of magnitude higher than that of a Boolean network. Most likely, power consumption of any spin-wave based device is dominated by the input / output apparatus [27]. New physical effects (such as non-local spin injection) could boost high power efficiencies, at least at the input side [28].

2.3. Spin waves for transmitting information

One of the earliest concepts for application of spin waves in microelectronics was based on the recognition that they may provide superior, wideband, short-range interconnections [29] akin to an on-chip photonic structure. This argument was later debated for metallic spin-wave conductors [30] – but it is possible that spin-waveguides made from low-damping magnetic materials significantly outperform metallic interconnects [31].

3. Boolean computing protocols based on spin waves

Just as in the case of photonic devices, one route to the design of wave-based logic gates is a Mach-Zender

interferometer-like structure. A recent implementation is illustrated in Fig. 2. Spin waves may interfere constructively or destructively, depending on the phase relation of the inputs [32], or possibly due to external, current-induced fields [33]. The relation between the input phases and the output amplitude (or phase) maps to a majority gate, which is a universal building block for logic devices.

Figure 2: Example of Boolean spin-wave based processing, taken from [32].

A different approach is to realize the magnonic equivalent of a transistor [34], which can be done exploiting the nonlinearity of magnon-magnon scattering.

It is important to keep in mind that the realization of a Boolean computing system requires a lot more than stand-alone logic gates. Some system components (such as a beam splitter [35]) were demonstrated, others were not. A useful guide here is the 'five tenets' of computing (see e.g. [36]), i.e. (1) nonlinear device characteristics, (2) complete set of Boolean operators, (3) output of one device can drive the next one, (4) input / output isolation and (5) power gain. The Boolean logic gates demonstrated so far certainly satisfy (1) and (2), but practical implementations to (3), (4) and (5) remain a challenge. It is straightforward to realize gain and isolation using electrical circuitry, but it is likely that a practical computing system should try to minimize the number of magneto-electric conversions and the five tenets should be fulfilled by spin-wave based constructions.

4. Spin-wave based, non-Boolean devices

Special-purpose, non-Boolean computing units may avoid the above-mentioned challenges associated with the interconnections of logic blocks. If a non-Boolean computing unit performs a high computing function (i.e. something that is way beyond the function of a simple logic gate) and this requires only relatively few inputs and outputs, then the input / output bottleneck may be less severe. We exemplify the construction of non-Boolean computing blocks

below. These devices are based on optical computing primitives, i.e. they use SWs to replicate the functionality of a certain optical processing tasks.

Figure 3a shows a high-level schematics of the spin-wave based processor. The device realizes a vector-vector mapping: electrical inputs generate a spin-wavefront with a well-defined amplitude and phase distribution and under the influence of local effective field distribution the result of the mapping (computation) is a SW intensity distribution, which is converted to an electrical signal for further processing.

A possible, immensely useful non-Boolean operation is analog Fourier transform. It is well known from optics [6] that a convex lens can generate the Fourier transform of the coherent light distribution. In SW-optics, one can use a concave (effective) field distribution to generate the same diffraction pattern [37]. Figure 3b) shows the magnetization distribution on the computing layer, as calculated from micromagnetic simulations. The SW lens is a planar structure, i.e. SW propagation in 2D is used to transform a one-dimensional vector. This particular SW structure was proposed in [37], and a very similar structure was experimentally realized in [38].

Figure 3: a) Spin-wave lens schematics b) Micromagnetic simulation of spin-wave distribution, as shown in [37].

The structure of Fig. 3 is still somewhat heavy on inputs and outputs: a say, 64-point Fourier transform requires 64 analog input points, where spin-wave intensity can be individually controlled and the same number of output, where the SW intensity can be measured and converted to electrical signals. Still, such a device can perform Fourier transforms in a single step, with several gigasamples per second speed and potentially replacing several thousands of individual logic gates [39].

Another approach to non-Boolean vector-vector mapping relies on crossbar-like structures of magnetic waveguides [40]. Depending on how the SW phase is altered at the crossings, these devices can also make complex linear transforms between their inputs and outputs in a single step. Elementary steps of holographic pattern matching and prime factorization [41] have been experimentally demonstrated in this scheme. One may construct a variety of interconnection / processing schemes in this spirit [42].

The number of spin-wave inputs can be drastically re-

duced and their structure simplified if the Fourier transform of a time-domain signal is of interest [27][43]. This can be done by a spin-wave-based implementation of the Rowland circle spectrograph is shown in Fig. 4. A single microwave stripline (antenna) is run along the serrated edge of a magnetic film. The clogged film edge simultaneously acts as a source of spin waves and as a diffraction grating. Since the diffraction grating is curved, spin waves with different wavelengths are eventually focused into different points along the so-called Rowland circle. If the current of the microwave transmission line is composed of multiple frequency components, those frequency components will generate spin waves with different wavelengths, and the multitude of frequency components will eventually be focused at different points along the output (the so-called Rowland circle). The device acts as a spectrum analyzer - a critically important and ubiquitously used component in signal processing and RF front-ends.

Figure 4: Schematics of a spin-wave based spectrum analyzer. The main component of the device is a curved diffraction grating, shown at the left of the image. Schematics of the I/O structures are overlaid on a micromagnetic simulation of the device. Taken from [27].

These above described 'quasi-optical' devices rely on spin-wave interference pattern formation. It is also possible to use spin waves solely as an interconnection between spin-based electronic devices and implement non-Boolean functions this way. For example, spin-wave based synchronization of spin-torque oscillators (STOs) have been proposed for vector-vector distance calculation [44] [45] [46][47], which is another ubiquitously used computing primitive in image processing. There is a large number of promising spin-torque building blocks [48], and in metallic ferromagnets SWs could substitute short-range electrical interconnections

5. Enabling technologies spin-wave devices

The last few years have seen a tremendous progress in the technologies leading towards spin-wave devices. Perhaps one of the most important of those is the availability of high-quality (low damping) sputtered YIG films [49], [50]. The quality of sputtered YIG films now rivals that of epitaxially-grown YIG, and chances are that such that

YIG (a brittle, hard to work with material) can be one day compatible with well-established microelectronic technologies. A major step in this direction is the recent result to grow YIG films on silicon substrate [51].

YIG is not the only material that may serve as spin-wave channel in SW devices. Cobalt-Iron compounds exhibit very low damping at specific composition [52] - and CoFe would be readily integrable with microelectronic devices. The high group velocity of spin waves in CoFe thin films [53] is beneficial for the envisioned high-frequency applications. Barium hexagonal ferrite (BaM) combines low damping and strong perpendicular magnetic anisotropy [54]. Almost all SW-based devices require an external magnetic field for their operation, but sufficiently strong anisotropy, which is seen in BaM can substitute cumbersome permanent magnets.

6. The main challenge: magneto-electric interfaces

As it was argued above, the Achilles's heel of SW-based devices (and, for that matter, most magnetoelectronic devices) is the input / output: the eventual practicality of these devices hinges on whether one can find energy-efficient, compact structures to convert electrical signals into spin-wave signals and vice versa.

Spin-wave excitations can be straightforwardly created by the Oersted field of waveguides. This is not a particularly power efficient method - the vast majority of the power pumped in the microwave transmission line is lost on the terminating resistance, and only a few percent of the energy is taken away by the spin waves [27]. Another challenge is the generation of short-wavelength spin waves, which is important in microelectronic applications - the non-localized field distribution of a typical micron-width transmission line couples poorly to submicron-width SWs. Alternatively, spin-torque oscillators are excellent sources of short-wavelength SWs in metallic thin-films [55] [56] [57], and they may be used on magnetic insulators as well [19] [58]. A third possibility is to use magnetostriction [59] - this could potentially be very energy efficient, as only electric field (and no DC current flow) is used for inducing spin-waves. One may use wavelength conversion to squeeze SW wavelength [60] or patterned multilayer structures [31] or nanoscale domain structures [61] to generate localized sources.

Spin-hall effect (SHE) -based manipulation of magnetization [62] and spin-pumping [63] are perhaps the most application-friendly way to generate SWs, especially in magnetic insulators. Spin-pumping materials (such as Pt) are highly resistive, which can be a problem for targeted low-power applications.

Waveguide, STO or SHE based SW generation all typically require currents on the order of milliamperes, and consequently, spin-wavefronts or spin-wave point sources (in case of an STO) can be created by power on the order of milliwatts. Recent experimental results point toward possibly much more power-efficient ways [28].

SW can be converted to electrical signals by magnetoresistive structures or (in case of magnetic insulators) via antennas or inverse SHE [64]. In all cases one typically expects signals in the few microvolt - few ten microvolts range [27]. DC readout of such signals is straightforward, but requires significant amplification before signals can be sent for further processing. In a practical scenario, however, one should pickup these signals with a significant (few ten megahertz to gigahertz) bandwidth - this requires carefully matched, low-impedance antennas, amplifiers and appropriate mixers [27]. It is expected that the SW readout will dominate the complexity and power consumption of SW-based processing systems.

7. Outlook

Spin waves have the potential to make a big hit in future data processing - they can combine the best of electronics and photonics and do it in an on-chip and integrable way. However, copying successful approaches from microelectronics may not be the best way toward spin-wave based computing, as the resulting circuits tend to require too many conversions between the electric and magnetic domains, introducing serious complexity and power bottlenecks. Spin-wave-based protocols will shine if complex processing tasks can be made without leaving the spin-wave domain, and construction of devices for non-Boolean computing primitives could be a way toward this goal.

There are many intriguing possibilities we did not even mention in this article: such as using nonlinear effects for computing, quantum circuits [65], or the possibility of using spin waves all the way up to the terahertz range [66].

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