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Magnonic logic circuits

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Abstract
We describe and analyse possible approaches to magnonic logic circuits and basic elements required for circuit construction. A distinctive feature of the magnonic circuitry is that information is transmitted by spin waves propagating in the magnetic waveguides without the use of electric current. The latter makes it possible to exploit spin wave phenomena for more efficient data transfer and enhanced logic functionality. We describe possible schemes for general computing and special task data processing. The functional throughput of the magnonic logic gates is estimated and compared with the conventional transistor-based approach. Magnonic logic circuits allow scaling down to the deep submicrometre range and THz frequency operation. The scaling is in favour of the magnonic circuits offering a significant functional advantage over the traditional approach. The disadvantages and problems of the spin wave devices are also discussed.

1. Introduction

There is an immense practical need for novel logic devices capable of overcoming the constraints inherent to conventional transistor-based logic circuitry [1]. After decades of miniaturization, there is still plenty of room for scaling down the size of the metal-oxide-semiconductor field effect transistor (MOSFET) and for increasing the device density in the complementary metal-oxide-semiconductor (CMOS) logic circuits. However, it is widely believed that further MOSFET shrinkage will be inefficient due to the power dissipation problem. Besides that, the growing number of devices per unit area results in tremendous difficulties with interconnection wiring [2]. Impedance match between devices and wires is another serious issue. A radical solution to the above-mentioned problems would be the development of transistor-less logic circuits implementing more efficient mechanisms for information transmission and processing. In this work, we consider magnonic logic circuits as one of the possible routes.

Spin wave (magnons) as a physical phenomenon has attracted scientific interest for a long time [3]. Spin wave propagation has been studied in a variety of magnetic materials and nanostructures [4–6]. Relatively slow group velocity (more than two orders of magnitude slower than the speed of light) and high attenuation (more than six orders of magnitude higher attenuation than for photons in a standard optical fibre) are two well-known disadvantages, which explain the lack of interest in spin waves as a potential candidate for information transmission. The situation has changed drastically as the characteristic distance between the devices on the chip entered the deep-submicrometre range. It has become more important to have fast signal conversion/modulation, while the short travelling distance compensates slow propagation and high attenuation. From this point of view, spin waves possess certain technological advantages: (i) spin waves can be guided in the magnetic waveguides similar to the optical fibres; (ii) spin wave signal can be converted into a voltage via inductive coupling; (iii) magnetic field can be used as an external parameter for spin wave signal modulation. The wavelength of the exchange spin waves can be as short as several nanometres, and the coherence length may exceed tens of micrometres at room temperature. The latter translates into the intriguing possibility of building scalable logic devices utilizing spin wave inherent properties.

The first working spin-wave based logic device has been experimentally demonstrated by Kostylev *et al* [7]. The authors used the Mach–Zehnder-type current-controlled spin wave interferometer to demonstrate output voltage modulation as a result of spin wave interference. This first working prototype device was of considerable importance for the development of magnonic logic devices. The device operates in the GHz frequency range and at room temperature. This immediately made it a favourite among the other proposed spin-based logic devices. Later on, exclusive-not-OR and

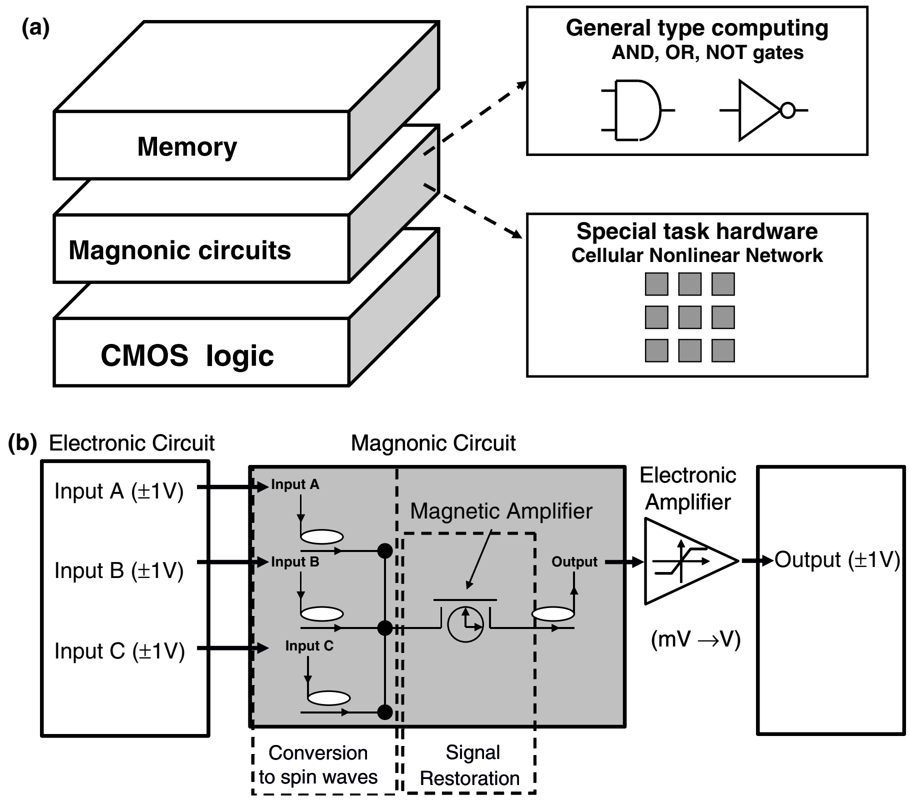

Figure 1. (*a*) Schematic of a 3D architecture comprising functional layers of conventional CMOS-based circuits, magnonic devices and a memory array. The magnonic circuit can be used for general computing (NOT, OR, AND gates) or as a complementary logic block (Magnetic Cellular Nonlinear Network) designed to perform special tasks such as image processing and speech recognition. (*b*) The communication among the functional layers is via electric signals (e.g. voltage/current), while the operation within the magnonic circuits is via spin waves only. The input data for the magnonic layer are received from the electronic part in the form of voltage pulses and converted into spin waves. The data processing in the circuit is accomplished by manipulating the amplitudes and/or the phases of the propagating spin waves. The result of computation is converted back to a voltage signal provided to the next electronic circuit.

not-AND gates have been experimentally demonstrated on a similar Mach–Zehnder-type structure [8]. The complete set of logic devices such as NOT, NOR and AND based on Mach–Zehnder-type spin-wave interferometer devices has been proposed [9]. In the above-cited works [7–9], spin wave amplitude is used to define the logic state of the output.

Another approach to spin wave based logic circuits utilizing phase as a state variable has been proposed [10] and then experimentally realized [11, 12]. Within this approach, a bit of information is assigned to the phase of the propagating spin wave. An elementary act of computation is associated with the change in the phase of the propagating spin wave. The latter provides an elegant solution to the NOT and Majority logic gate construction. Each of the proposed approaches has certain advantages and shortcomings. The rest of the paper is organized as follows: in the next section, we describe possible approaches to magnonic logic circuits for general computing and special task data processing. In section 3, we analyse the basic elements required for magnonic circuits. Discussion and conclusions are given in sections 4 and 5, respectively.

2. Possible approaches to spin-wave logic circuits for general computing and special task data processing

The general idea of using spin wave based logic circuit is to use spin as a state variable instead of charge, and to transmit and process information by exploiting wave phenomena, without the use of electric current. The latter may provide an advantage over the existing charge-based CMOS circuitry. At the same time, the proposed spin wave devices must be compatible with conventional electron-based devices enabling efficient data exchange. It is difficult to expect that magnonic logic devices will be more efficient than scaled CMOS in all figures of merit (e.g. speed of switching). However, it may be a complementary part to the traditional approach offering a low-power consuming hardware for general and special task data processing. Figure 1 schematically shows a three-dimensional architecture comprising functional layers of conventional CMOS-based circuits, magnonic devices and memory arrays (e.g. magnetic random-access memory). The communication among the functional layers occurs via electric signals (e.g. voltage/current), while the operation within the magnonic circuits occurs via spin waves only. The input data for the magnonic layer are received from the electronic part in the form of voltage pulses and subsequently converted into spin waves. The magnonic circuit can be used for general computing (NOT, OR, AND gates) or as a complementary logic block (Magnetic Cellular Nonlinear Network) designed to perform special tasks such as image processing and speech recognition. The data processing in the circuit is accomplished by manipulating the amplitudes and/or the phases of the propagating spin waves. Finally, the result of computation

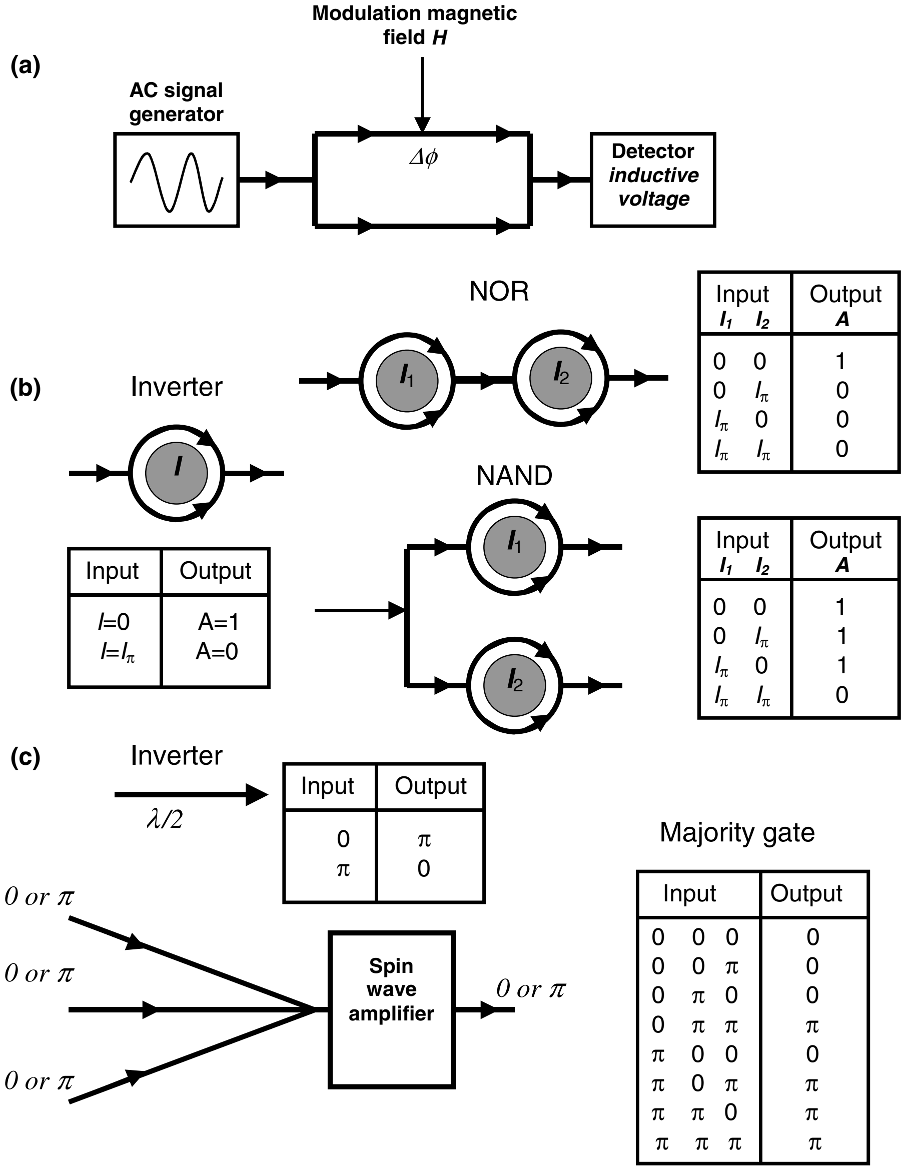

Figure 2. Possible approaches to general type computing. (*a*) Mach–Zehnder-type spin wave interferometer. The phase shift in one of the interferometer's arms is controlled by an external magnetic field. The output voltage is a function of the relative phases of the two interfering spin waves. (*b*) A set of logic gates (NOT, AND, OR) for general type computing based on the Mach–Zehnder interferometer structure. A bit of information is assigned to the amplitude of the propagating spin wave. (*c*) A set of logic gates (NOT, Majority) for general type computing utilizing phase for information encoding. Two relative phases of '0' and 'π' are used to represent logic states 0 and 1, respectively. Logic functionality is achieved by changing the phases of the propagating spin waves.

is converted back to a voltage signal and may be provided to the electronic part.

Possible schemes for general type computing are shown in figure 2. In figure 2(*a*), the scheme of the first prototype device is shown [7]. It consists of the specially configured magnetic waveguide, transducer and receiver placed at the edges of the waveguide and a control-current stripe conductor. The structure resembles a Mach–Zehnder interferometer with a controlled phase shifter. A spin wave signal is excited in the waveguide by the microwave pulse. The spin wave propagates through the waveguide and becomes split into two paths as shown in figure 2(*a*). There is a control-current stripe conductor placed under one of the paths. An electric current passed through the conductor produces a magnetic field and, thus, affects the propagating spin wave. The logical output is the amplitude of the mixer signal, which is a function of the modulating electric current. Different logic gates can be constructed by adjusting specific phase shifts for the propagating spin waves [8].

An example of the complete set of logic gates based on the Mach–Zehnder interferometer structure as proposed in [9] is shown in figure 2(*b*). The main building block is a miniature Mach–Zehnder interferometer with a vertical current-carrying wire. The area of the interferometer can be as small as 300 nm × 300 nm. With a zero current applied, the spin waves in two branches interfere constructively and propagate through. The waves interfere destructively and do not propagate through the structure if a certain electric current

I_π is applied. It should be noted that in the considered scheme the input logic state is represented by the amplitude of the electric current and the output state is assigned to the amplitude of the spin wave signal A, which implies an additional element for spin wave to electric current conversion. At some point, this device resembles the classical field effect transistor, where the magnetic field produced by the electric current modulates the propagation of the spin wave—an analogue to the electric current.

Another approach to magnonic logic circuits has been proposed in [10, 13, 14]. In this approach, a bit of information is encoded into the phase of the spin wave. Two relative phases of '0' and 'π' are used to represent logic states 0 and 1, respectively. The utilization of phase for information encoding offers an original way to NOT and Majority logic gates construction as illustrated in figure 2(*c*). The inverter is just a waveguide of the length $\lambda/2$, where λ is the wavelength of the spin wave. A spin wave propagating through such a waveguide accumulates a π-phase shift, which corresponds to the inverter logic function. The Majority logic gate can be realized as an odd-number wave combiner followed by a spin wave amplifier. The input spin waves have the same frequency and may have only two possible initial phases: 0 or π. The phase of the output spin wave (spin wave propagating through the combiner) corresponds to the majority of the input phases. Depending on the number of waves coming with the same phase, the amplitude of the output spin wave may vary. The spin wave amplifier is aimed to amplify and equalize the amplitude of the output signal. A prototype device exploiting only two spin wave phases has been experimentally demonstrated [11, 12]. In this device, the initial phase of the excited spin wave signal is controlled by the polarity of the electric current in the excitation contour. The direction of the electric current through the excitation line (clock-wise or counter clock-wise) defined the relative phase between two excited spin waves. The main potential advantage of the phase encoding approach is that different frequencies can be used as separate information channels allowing parallel data processing in the same device structure. For each frequency, logic zeros and ones are attributed to the phases and, then, can be processed independently for each frequency. The experimental data presented in [12] show the possibility of device operation in a certain frequency range. The ability to transmit and process information in a multi-channel manner opens a new horizon for building logic circuits with capabilities far beyond the limits of the von Neumann architecture.

There are special data processing tasks such as image processing and speech recognition, which require a certain set of operations to be applied to large data strings. A general-purpose processor performs these tasks in a sequential manner consuming a significant amount of time and memory resources. To speed up the computational process a special type of hardware is needed. One of the most promising architectures is a Cellular Nonlinear Network (CNN) first formulated by Leon Chua [15]. CNN is as a two (three or more) dimensional array of mainly identical dynamical systems, called cells, which satisfy two properties: (i) most interactions are local within a finite radius R and (ii) all state variables are signals of continuous values. An example of magnetic CNN with spin wave bus has been described in [16]. The main expected advantages of using spin waves are the following. First, the radius of interaction among the magnetic nano-cells R can be of the order of micrometres and limited only by the spin wave attenuation length. Second, an external magnetic field can be used to control the information exchange among the cells. The latter provides a mechanism for a number of logic functions to be performed in one structure without rewiring/reconfiguration.

The schematic of the magnonic CNN is shown in figure 3. There is a two-dimensional array of memory cells sharing a common magnetic layer—the spin wave bus. The elementary cell is a bi-stable element with two preferable magnetic polarizations. In contrast to the well-known Magnetic Quantum Cellular Automata [17], the cells interact with each other indirectly via the spin waves. Each cell in the array emits and receives spin waves produced by the other cells. It is assumed that the cell state can be changed by the incoming spin waves. Then, the final state is defined by the sum of all incoming spin waves. In this scenario, each cell acts as a Majority logic gate. Taking into account that spin wave propagation is sensitive to the external magnetic field, it is possible to govern the operation of the whole network by one external parameter—magnetic field. The examples of image processing by magnetic CNN have been presented [18]. A set of image processing functions such as filtering, dilation, erosion, vertical and horizontal line detection can be realized on one template without rewiring or reconfiguration but with a proper choice of the strength and direction of the external bias magnetic field. According to estimates [18], magnonic CNN with spin wave bus may have a 10^9 cells per cm^2 cell density and accomplish data processing in a parallel manner with GHz frequency.

There are other possible schemes proposed for magnetic networks with spin wave bus [19, 20]. The main motive of the spin wave-based architectures is to exploit wave phenomena for data transmission and parallel data processing. The latter is an advantage inherent to all wave-based architectures. The specific benefits of using spin waves are short wavelength, compatibility with magnetic memory and the ability to control functionality by one global parameter—magnetic field. Practical implementations of the proposed circuits depend on the progress in the spin wave devices development. In the next section, we describe and analyse the basic components to be used as building blocks for general and special task logic circuits.

3. Basic elements for magnonic logic circuits

There are several basic elements required for spin wave logic circuit construction: converters to translate electric signals into spin wave and vice versa, a waveguide structure including combiners and splitters, a spin wave amplifier, a memory cell that can be switched by a spin wave (e.g. multiferroic cell) and a phase modulator to provide a controllable phase shift to the propagating spin wave. In this section, we review possible

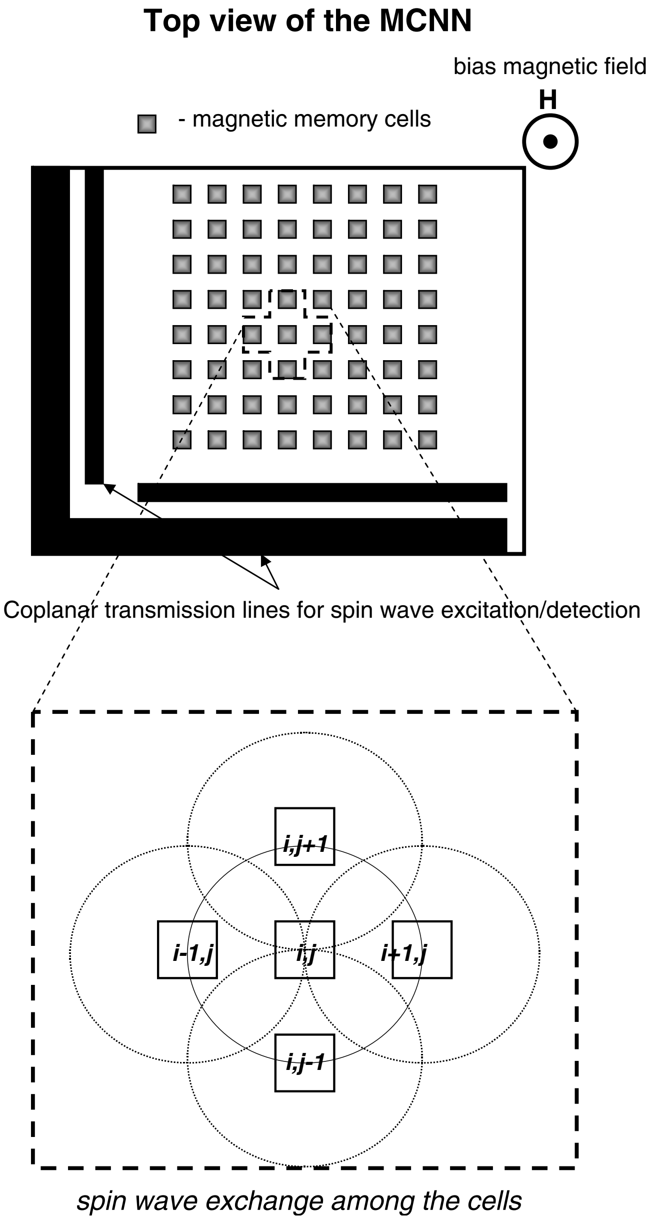

Figure 3. Schematic of the magnonic CNN for special type data processing. The core of the CNN consists of a two-dimensional array of magnetic memory cells sharing the common magnetic layer—spin wave bus. The elementary cell is a bi-stable element with two preferable magnetic polarizations. The cells communicate via spin waves propagating in the spin wave bus. Each cell changes its state according to the sum of all incoming spin waves. External magnetic field is used as a global parameter to govern network operation.

approaches to the following devices and define most important parameters for application in logic circuits.

Conducting contours (e.g. microstrips, coplanar transmission lines, etc.) are the most convenient and widely used experimental technique for spin wave excitation, and detection [4, 5, 21]. Two contours are placed in the vicinity of the magnetic film. One of the contours is used as a transducer and the second one as a receiver. Ac electric current is passed through the transducer generating a magnetic field. In turn, the magnetic field excites spin waves in the magnetic layer. The receiver detects the inductive voltage produced by the propagating spin waves. The main advantage of this technique is fabrication simplicity. It is convenient to use inductive coupling and convert the spin wave signal into the voltage pulse. At the same time, there are certain technological constraints inherent to this technique primarily due to the direct inductive coupling. The transducer and receiver are coupled via the stray field due to the close proximity. The strength of the direct coupling may exceed the spin wave signal and increases as the size of the magnetic circuit is scaled down.

Spin waves can also be excited by the spin-polarized currents injected into a ferromagnetic film due to the transfer of the spin-angular momentum as it was theoretically predicted [22, 23]. The interaction between spin waves and itinerant electrons is prominent near the interface between the non-magnetic and ferromagnetic layers. The amplitude of the excited spin waves grows as the current density through the interface exceeds a certain critical value. This phenomenon has been experimentally verified in Co/Cu multilayered structures showing high frequency 40–60 GHz current-driven spin wave excitation [24]. Spin wave excitation by the spin-polarized electric current has certain technological advantages and shortcomings. On the one hand, spin wave excitation via spin torque requires only point contacts (characteristic size of the order of tens of nanometres), which is in favour of scalable devices. The high-frequency operation is another advantage of the spin torque mechanisms. On the other hand, the overall energetic efficiency may not be high. The threshold current density required for spin wave excitation is higher than 10^6 A cm^{-2}, which implies high operational power. At this moment, it is not clear how much of the consumed power can be transferred into a specific spin wave mode.

The problem of the input/output isolation can be resolved by using different mechanisms for spin wave excitation and detection. For example, the excitation can be done by a spin torque oscillator while the detection is by the inductive coupling. The most important parameters to be taken into account when comparing different approaches to the converters are scalability, energetic efficiency and the ability of high-frequency operation. Some of the previously developed techniques (e.g. spin wave excitation by using parametric pumping in a micro-cavity) may not sustain the scaling trend. The novel proposed approaches based on the spin torque effect or magneto-electric coupling have to be studied to clarify energetic efficiency and high-frequency operation, respectively.

The next element to be discussed is the magnonic waveguide. Although there have been an increasing number of experimental studies on spin wave propagation in micrometre and submicrometre structures during the past decade [5, 25–27], the engineering of magnonic waveguides is mainly an unexplored area. The essential requirement for the waveguide structures in a logic circuit is providing spin wave propagation with maximum group velocity and minimum attenuation. The main questions are related to the proper choice of the magnetic material and the optimum waveguide structure. Yttrium-iron-garnet (YIG) and permalloy (NiFe) were used in the demonstrated prototypes [7, 11]. Having the same order of magnitude maximum propagation speed, spin waves in non-conducting ferrites possess lower attenuation than in the metallic ferromagnets. On the other hand, the fabrication of a ferrite waveguide such as YIG requires a special gadolinium gallium garnet (GGG) substrate. In contrast, a permalloy film can be deposited onto a silicon platform by using the sputtering technique [11]. The latter is in favour of using permalloy and other metallic ferromagnetic materials (e.g. CoFe, CoTaZr), whose fabrication technique is compatible with silicon technology.

Artificial magnetic structures with periodically modulated properties, so-called magnonic crystals, are of great promise for potential use as magnonic waveguides. Periodic boundary conditions affect spin wave propagation resulting in significant dispersion modification [28]. The latter can be used as a tool for transport parameters optimization. Magnonic crystals can be fabricated as a composition of two materials with different magnetic properties or as a single material waveguide with periodically varying dimensions. Frequency band gaps have been experimentally observed in a grating-like structure comprising shallow grooves etched into the surface of an yttrium-iron-garnet film [29], in a one-dimensional array of permalloy nanostripes separated by the air gaps [30] and in a synthetic nanostructure composed of two different magnetic materials [31].

The dispersion modification can be used to enhance the efficiency of the converters, minimize the undesirable coupling with outer devices and to reduce the damping for information-carrier modes. According to the theoretical study [32], the efficient damping coefficient in magnonic crystals depends strongly upon the spin wave frequency and the bias magnetic field. It would be of immense practical benefit to engineer magnonic waveguides with suppressed damping by the proper choice of the magnetic parameters.

An original approach to magnonic circuit interconnection may come from the utilization of spin wave self-focusing in magnetic films [33]. The self-focusing of a moving wave pulse in two spatial dimensions and the formation of localized two-dimensional wave packets was experimentally observed [33]. Recently, the periodic self-focusing of spin waves propagating in permalloy microstripes [34], and the transformation of propagating spin-wave modes in permalloy waveguides with variable width was also found [35]. These experiments show the possibility of the effective control of the spin-wave propagation due to the variation in the internal demagnetizing fields. The latter provides a mechanism to focus the spin-wave energy in certain space regions within a continuous magnetic film. The use of self-focusing may be an elegant way of making magnonic splitters and combiners.

The implementation of complex logic architectures for parallel data processing described in section 2 would require a special type of memory, which can be switched by spin waves. To the best of our knowledge, such a memory element has never been experimentally demonstrated. In principle, the inductive voltage produced by the propagating spin wave can be amplified to switch a conventional electron-based memory. An example of spin wave bus integration with a bi-stable electronic element based on resonant-tunnelling diodes is described in [13]. The disadvantage of this approach is associated with the number of elements per elementary cell, which would require several magnetic and electronic components. Another possible approach to the spin wave driven memory is in the use of a multiferroic structure. There is a growing interest in multiferroics—a special type of materials possessing electric and magnetic polarizations at the same time [36]. The electric and magnetic properties in multiferroics are related to each other via the internal magneto-electric coupling. It is possible to change magnetic polarization by electric field and vice versa. The electrical control of the antiferromagnetic domain structure in a single-phase multiferroic material at room temperature has been demonstrated [37]. The latter offers a promising approach to a new type of magnetic memory. An example of a multiferroic memory cell, which can be switched by a spin wave, is proposed in [14]. The proposed memory cell is a multilayer structure comprising a metallic ferromagnetic material (e.g. NiFe), a piezoelectric layer (e.g. PZT) and a non-magnetic metallic layer (e.g. Al). The conducting ferromagnetic layer and the top electrode serve as two sides of the parallel plate capacitor filled with the piezoelectric. An electric field applied across the piezoelectric layer produces stress. In turn, the stress results in the rotation of the easy axis in the ferromagnetic material under the piezoelectric. Theoretically, such an element can be switched by a spin wave(s) at the time of the easy-axis rotation [14]. A two-phase magnetoelectric CoPd/PZT cell was experimentally demonstrated by Sang-Koog *et al* [38], and a rotation of the easy axis rotation up to 150° was observed. The utilization of multiferroics may provide a route to scalable and multi-functional magnetic devices. The main concern is related to the maximum switching frequency, which can be practically achieved.

In order to build logic circuits with a large number of components and compensate losses during spin wave propagation, one needs to introduce a spin wave amplifier. There are several well-known mechanisms, which can be used for spin wave amplification. For example, a spin wave can be amplified by passing an electric current through a conducting magnetic material along with the direction of spin wave propagation [39]. A spin wave can also be amplified by an alternating magnetic field, via so-called parametric microwave pumping [40, 41]. A microstrip structure can be used as a generator of ac magnetic field operating at the parametric resonance frequency $\omega = 2\omega_0$, where ω_0 is the frequency of the spin wave signal. Parametric microwave spin wave amplifiers showing a gain coefficient up to 40 dB have been experimentally demonstrated [40, 42–44]. Nonlinear interactions of spin waves with a microwave magnetic field of parametric electromagnetic pumping manifests itself in a variety of interesting physical phenomena, which stimulate the active study of this process [45, 46]. However, the use of the microwave pumping has some technological disadvantages associated with the size of the amplifier and/or the energy losses via the stray field. It would be beneficial from the practical point of view to use a local amplifier to restore spin wave amplitude at a certain point of the magnetic circuit. An example of such an amplifier has recently been proposed [47].

The amplification of the spin wave amplitude may be achieved via the magneto-electric coupling in an artificial two-layer multiferroic structure, which comprises piezoelectric and ferromagnetic materials. According to numerical estimates [47], the multiferroic amplifier may have high energetic efficiency converting more than 90% of the consumed power into a spin wave signal. However, no prototype device has been realized so far.

Another possible mechanism for spin wave amplification is through stimulated emission by the spin torque oscillators. Previously, we have mentioned the possibility of using spin-polarized current for spin wave excitation. The same devices under certain conditions can be used for spin wave amplification. From the theoretical point of view, the spin damping may become negative as the current density through the interface exceeds some critical value. The amplitude of the spin wave propagating through such a region with a negative damping would increase exponentially. With a proper design of the spin wave resonator, the latter may lead to the stimulated spin wave emission analogue of the injection laser or SWASER (spin-wave amplification by stimulated emission of radiation) proposed in [48]. Again, the main unknown parameter for spin-torque devices is the practically achievable energetic efficiency, which is of considerable importance for low-power consuming logic devices.

A phase modulator is an element aimed at providing a π-phase shift to the propagating spin wave. The operation of the interferometer-based logic devices [7–9] depends on this element. A reconfigurable magnonic circuit would also require such an element [14]. The phase shift can be introduced by an external magnetic field as it was realized in the first prototype logic circuit [7]. The main requirements for the phase modulator are scalability and low power consumption. The use of external magnetic field produced by an electric current in the conducting substrate may not be efficient from this point of view. The scaling down of the length of the interferometer will require an increase in the electric current to provide a stronger magnetic field. This problem may be solved in part by using the optimized structure presented in [9]. It should be noted that the phase shifters used in the interferometer-based circuits [9] and shifters used for circuit reconfiguration [14] have different operational frequencies. The shifters used in the interferometers-based switches may be needed in every computational step and have to sustain high-frequency operation. In contrast, circuit reconfiguration occurs on a much longer time scale. In this case, a non-volatile element such as a domain wall can be used to provide constant phase shift for a relatively long period of time.

4. Discussion

The utilization of the magnetization as a state variable offers a certain advantage over the conventional charge-based approach. Both the amplitude and the direction (phase) of the magnetization can be used for information encoding in contrast to a scalar charge. As we discussed in section 2, a bit of information can be encoded into the amplitude or the phase of the spin wave signal. There are certain pros and cons for each approach. The encoding into the amplitude immediately leads to a 'spin wave switch'—a device, which can transmit or stop the propagating spin wave. An example of such a device is described in [9]. It is not clear whether the 'spin wave switch' may offer a significant advantage over the CMOS in terms of scalability and switching speed. The main expected benefit for this device is low power consumption due to the low energy of the spin wave signal [9]. In our opinion, the phase encoding is a more promising approach. Input data can be encoded into the relative phases of the spin wave signals (e.g. 0 and π). The result of computation can be recognized by the phase of the output spin wave signals. The phase of the propagating spin wave can be detected by the sign of the produced inductive voltage in the time-resolved measurements [5]. The latter provides a convenient mechanism for signal recognition and spin wave-to-voltage conversion at the same time. The main potential advantage of the phase encoding approach is that different frequencies can be used as separate information channels allowing parallel data processing in the same device structure. Logic zeros and ones are attributed to the phases and, then, can be processed independently for each frequency. The experimental data presented in [12] show the possibility of device operation in a certain frequency range. The ability to transmit and process information in a multi-channel manner provides a fundamental advantage over the existing switch-based logic circuitry and opens a new horizon for building logic circuits with capabilities far beyond the limits of the von Neumann architecture.

The utilization of phase for information encoding requires a non-linear bi-stable phase element, which provides the output on two possible phases. An example of such a device is the magnetic parametron, which has been invented and realized in the early days of magnetic computers more than fifty years ago [49]. Magnetic parametron is a resonant circuit in which the inductance is made to vary periodically at frequency $2f$ generating a parametric oscillation at the subharmonic frequency f. The subharmonic parametric has an important property in that the oscillation will be stable in either of two phases which differ by π radians with respect to each other. Parametron represents and stores one binary digit, '0' or '1', by the choice between these two phases, 0 or π radians. Under certain resonance conditions, the oscillation generated in the parametron is 'soft', that is, it is easily self-started from any small initial amplitude. In this case, the choice between the two stable phases of the oscillation having a large amplitude can be made by controlling the phases of the small initial oscillation. The first built magnetic parametrons consisted of coils, ferrite cores, resistors and transformers forming a resonant circuit adjusted to frequency f [50]. Ac electric current of $2f$ frequency was applied to one of the coils to excite the sub-harmonic oscillation. A complete logic circuit consisted of a number of inductively coupled magentic parametrons. It is interesting to note that in the earlier days of computer development, the parametron based magnetic computers competed with the transistor-based approach [49]. Evolving this old idea, the magnetic parametron logic circuits can be built by combining spin wave parametric amplifiers coupled via the specially designed waveguides. For example, the Majority gate shown in figure 2. comprises three merged waveguides and one parametric amplifier. Three spin wave signals are to provide the 'seed' small-amplitude signal to be amplified. The phase of the output corresponds to the majority of the input phases. The magneto-electric cell described in [14, 47] is another possible device allowing phase bi-stability. In the magneto-electric cell, the parametric amplification may be achieved via the magneto-electric coupling in an artificial two-phase multiferroic structure.

In order to find practical application, magnonic logic circuits have to show capabilities beyond the conventional CMOS-based logic circuits in terms of functional throughput, which is defined as a number of operations per area per time (Mops/cm^2/ns). The area of magnonic circuits is mainly defined by the wavelength of the information carrying spin wave. The length of the buffer gate has to be an integer number of the wavelength, which restricts the minimum circuit length to at least one wavelength. In the experimentally realized prototype devices [7, 8, 11], the operating wavelength was of the order of several micrometres. This quite long wavelength is due to the size of the transducer and receiver micro-antennas fabricated by the tools of optical lithography. Using nanotechnology, it is possible to scale down the size of the antenna and reduce the wavelength to a submicrometre range. The width and the thickness of the spin waveguides can be scaled down to several nanometres. One of the possible problems with nanometre-scale spin wave devices is defect tolerance. The permissible size variation of the spin wave components, which does not affect logic functionality, can be estimated as $\lambda/8$. Any defect of the waveguide structure with a characteristic size much smaller than the spin wavelength has no critical effect on spin wave propagation. Thus, there is a tradeoff between the scalability and the defect tolerance.

The time delay per spin wave circuit is the ratio of the circuit length and the spin wave group velocity v_g. The group velocity varies for different magnetic materials, waveguide dimensions, the strength and direction of the bias magnetic field [51]. Typically, its value is in the range 10^4–10^5 m s^{-1} for magnetostatic surface spin waves in conducting ferromagnetic materials, such as NiFe, CoFe and CoTaZr. In our estimates, we take 10^5 m s^{-1} as a benchmark value.

In figure 4, we present numerical estimates showing the functional throughput of the spin wave Majority logic gate, which can be used as AND or OR gate, and compare it with the conventional CMOS-based NOR gate. The throughput is plotted as a function of the minimum feature size, which is the gate length for CMOS and the wavelength λ for spin wave circuit, respectively. The throughput estimates for CMOS circuit are based on the available data [1]. The CMOS throughput is projected according to a general trend showing the circuit area scaling down by a factor 4 and the time delay scaling by a factor 0.7 for each new technology generation. The area A and the time delay $t$per magnonic circuit are estimated as follows: $A = 15\lambda^2$, and the time delay $t = 3\lambda/v_g$. The throughput estimates are done for one operation channel (frequency) only. As seen from figure 4, spin wave gate may provide significant throughput advantage (more than three orders of magnitude) over the CMOS circuit. This optimistic projection is due to the fact that the throughput of the spin wave circuit is inversely proportional to the wavelength in the cubic power, as the area and the time delay per spin wave circuit decrease with scaling down of the wavelength. However, the throughput of the experimentally demonstrated prototypes is far below the currently used CMOS circuitry. The scaling down of the wavelength to a deep submicrometre region is one of the main challenges for the spin wave logic devices. It should be noted that short wavelength spin waves (so-called exchange spin waves) differ significantly from the currently exploited magnetostatic waves enabling THz operation frequency, as pointed out in [52].

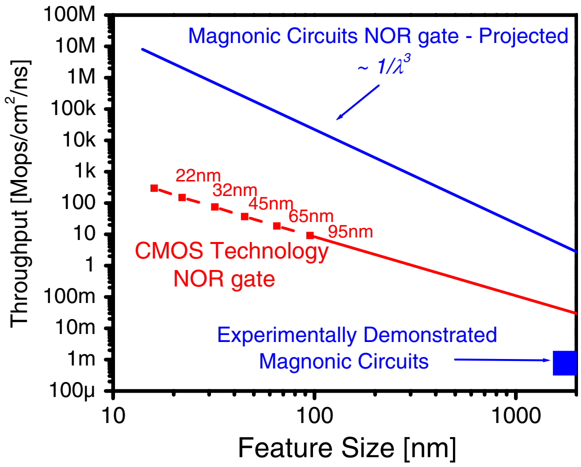

Figure 4. Numerical estimates on the functional throughput of the Magnonic majority logic gate (can be used as AND or OR gates) and conventional CMOS-based NOR gate. The throughput is plotted as a function of the minimum feature size, which is the gate length for CMOS and the wavelength λ for spin wave circuit, respectively. (This figure is in colour only in the electronic version)

There is one more argument in favour of spin wave logic devices. The Majority based logic is more powerful for implementing a given digital function with a smaller number of logic gates than CMOS [53]. For example, the full adder circuit may be constructed with three majority gates and two inverters. In contrast, a transistor-based implementation requires a larger circuit with seven or eight gate elements (about 25–30 MOSFETs) [54]. The advantage of the wave-based devices is even more significant for building more complex logic circuits.

Power consumption is a parameter, which is critical for nano-circuitry. Energy dissipation in magnonic logic circuits has never been the subject of a detailed study. On the one hand, the energy of the spin wave signal is limited by the thermal noise only and can be anywhere close to kT. For an acceptable error rate, it can be estimated about $20kT$ per bit. Although spin waves have a short attenuation length, the power dissipated in the waveguides may be orders of magnitude smaller than the Joule's heat in the best metallic wires connecting CMOSs. On the other hand, one will need a spin wave amplifier in order to provide fan out and build logic circuits consisting of a large number of components. Taking into account that today's CMOS-circuits dissipate about 10^6 kT per operation [1], even 1% efficiency for the spin wave amplifier would give an advantage over the CMOS technology. The development of high-efficient and scalable magnonic amplifiers is one of the important and necessary steps towards magnonic circuitry.

There are a number of problems to be solved before magnonic logic devices will be able to compete with CMOS-based circuits. Some of the described spin wave components such as the multiferroic memory cell has not been experimentally demonstrated. The design of the existing prototypes have to be optimized and improved in order to increase energetic efficiency and scale down the device area. Currently, the most challenging problem is associated with the inductive cross talk between the input and the output ports. The strength of the direct coupling via stray field exceeds the spin wave signal by several times in micrometre scale devices [11]. At this point, it is clear that the use of microwave field for spin wave generation does not fit the scaling requirements. The conducting contours used in the laboratory experiments should be replaced by the point contact devices such as spin torque oscillators or multiferroic elements. Then, all components of the spin wave circuit have to be impedance-matched to provide the maximum energetic efficiency and minimize losses. Without any doubt, the realization of the spin wave logic circuits would require considerable effort in the area of magnonics. Nevertheless, the advantages offered by the magnonic logic circuitry are significant enough to justify extensive research.

5. Conclusions

We have described and analysed possible approaches to magnonic logic circuits for general and special type computing. The distinctive feature of the considered schemes is that information is transmitted via spin waves. Both amplitude and phase of the propagating spin wave can be used for information encoding. We have described basic elements required for circuit construction. Some of these elements have been experimentally demonstrated and some of them are only proposed. The prototype micrometre scale spin wave logic devices realized so far show functional throughput, which had been reached by the CMOS circuitry 20 years ago. In order to compete with conventional logic devices, the operating wavelengths of the magnonic circuits have to be scaled down below a micrometre. The further scaling down to a deep submicrometre range is in favour for spin wave devices offering significant functional throughput enhancement over the conventional circuits. There are certain advantages of using the spin wave phase for information encoding. Logic circuits such as AND, OR gates can be realized with fewer elements than required for the switch-based circuitry. Besides that, the exploiting of wave superposition allows us to use different frequencies as independent information channels. The latter provides a fundamental advantage over the conventional CMOS-based logic circuits. There is a list of problems to be solved before magnonic logic circuits will be of practical value. Inductive cross-talk is one of them, requiring a radical change in the approach to input/output devices. The lack of experimental data does not allow us to conclude on the practically achievable power dissipation level. Notwithstanding these problems and concerns, magnonic logic devices offer an intriguing route towards integrated magneto-electronic circuitry with functional capabilities far beyond the conventional CMOS-based approach.

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