Contemporary Findings on Magnonics for Microwave Communication Systems

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Introduction

Processing and transmission of information signals have an attracted scientific interest in recent years [1-3]. Due to the recent developments in advanced nanofabrication technologies, there have been different types of nanoscale devices explored for the ultrafast information processing and ultrahigh density information storages. Microwave communication plays crucial role for processing and transmission of information signals around the world. The integration of nanofabrication technology and microwave communication has expeditiously stridden in the last two centuries lead to wireless communication which is the most significant achievement for today's modern electronics-based lifestyle. The advanced electronic gadgets repleted by the entire world which makes human lives more sophisticated and easier to access the machines and humans. This sophisticated life is possible due to the surge of the semiconductor era and advancement as well as scaling down transistors in the semiconductors industry attained exponential growth, which stills ruling the world [4-5]. However, the scaling dimension and integration have introduced a new challenge in electronics design i.e., heat dissipation and power consumption which are major hinders to enhancing device performance [6]. The limitations of using higher frequency in analog/RF application due to the materials' properties (mobility and saturation velocity) and device architecture affect the device performance [7]. Device engineers have been working on new materials (graphene), novel devices (FinFET, TFET, and HEMT), and new transport mechanisms (Tunneling and Ballistic) to overwhelm the issues as mentioned above [8-9]. However, the fundamental limitation of charge-based transport mechanism is questionable to address the future requirements. Thereby, many researches have been booming in recent decades, in which the magnetization dynamics in magnetic materials have resurged the fields of spintronics, and magnonics [10-11], which leads to rapid growth in signal processing and transmission technology. The intrinsic spin property of magnetic materials has been emerging in many scientific and industrial technology, and more new concepts begin in condensed matter physics. The ability to carry the information signals via spins would propagate over a long distance in nanostructured magnetic materials with minimal energy would be discussed in the field of magnonics [12] which paves path to make a remarkable breakthrough in data technology for storage and processing purposes [13].

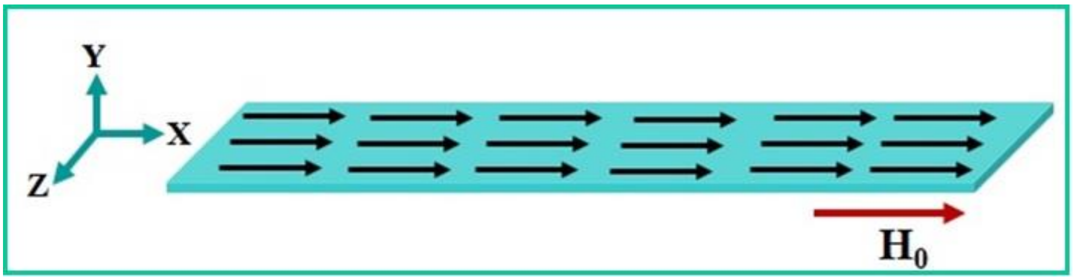

Figure 1: The pictorial representation of ground state of ferromagnetic materials.

The incipient of magnonics, a research field in nanomagnetism and nanoscience, addresses the spin waves (SWs) characteristics that can transmit, store, and process information. The concept of SWs as magnetization dynamics in a magnetically ordered medium (Ferromagnets) was first introduced by F. Bloch in 1932 [14]. In classical view, the phase-coherent precession of magnetization in ferromagnets can be represented as SWs [15-16]. For instance, the ground state of ferromagnetic material is depicted in Fig. 1, where the ordered alignment of spins are seen. The ground state of spins can be perturbed by applying an external field or current, which could be in the form of pulses. The external pulses produce the persistent precession of spins and the cumulative relies upon SWs. The quantum representation of SWs can be considered as magnons [15, 17] whose ability to carry the energy that describes the complete precession of individual spins over a chain, as shown in Fig. 2.

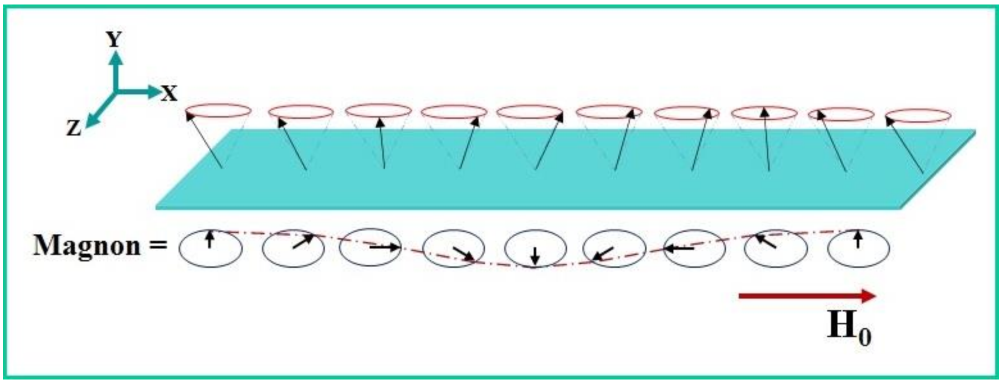

Figure 2: The cumulative of complete precession of individual spins refereed as SWs and the particle behaviour coined as magnon.

Figure 3 shows the advantages of SWs that have ability to exhibit the frequency in the range of GHz with low intrinsic energy. The SWs able to reach the high group velocity (V_g) in the range of (µm/ns) which is suitable for long range communication systems.

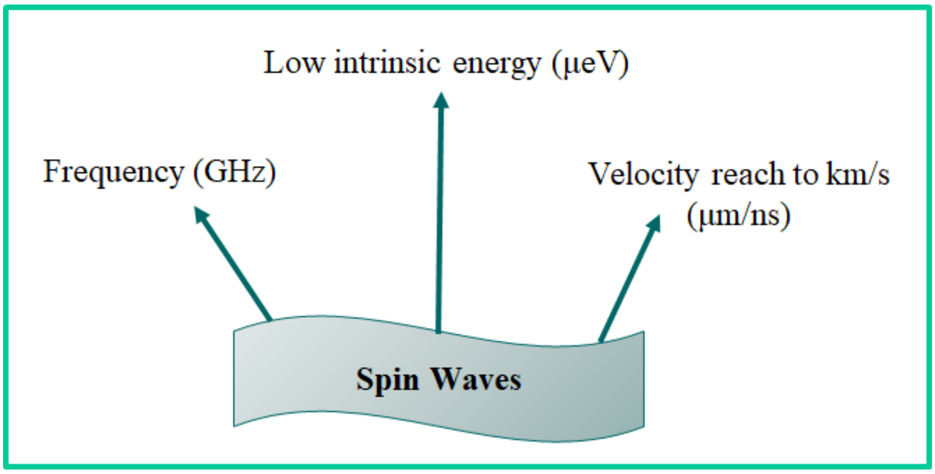

Figure 3: The advantages of SWs

The wave properties such as diffraction, refraction, reflection, tunnelling, excitation, and propagation of SWs [18] can act as the information carriers. The information can be encoded in SWs by using either its phase or amplitude. Typically, the persistent precession of SWs exhibits their frequency in the microwave regime offers special attention to possess the captivating potential microwave applications. Although the waves can propagate in the periodic modulation was recognized since 19th century [19]. The understanding of pass and stop bands for electromagnetic wave propagation was made known in 1950s [15,20]. Since after two decades, the idea of periodic modulation was imported into the magnetic systems. The SWs can propagate with information signals in periodic modulation of magnetic media that laid the invention of magnonic waveguides (MWs) in the late 1990s [21]. The information-carried SWs can be controlled, excited, propagated, and detected through periodic modulation on magnetic media by either passively (patterned structures, modulated magnetic properties) or actively (spin texture, electric field, magnetic field) manner [12]. The types of MWs are displayed in Fig. 4 where the planar nanostructured MW (Fig. 4(a)) which is in thin form. To enhance the filtering properties in MWs, the different shapes and sizes of antidots (airholes) can be incorporated in planar MWs, termed as magnonic antidot waveguides (MAWs) as shown in Fig. 4(b). Fig. 4(c) shows the bicomponent magnonic waveguides (BMWs) comprises of two different magnetic materials exhibit high V_g that highly suitable for long range communications. The various ways of controlled modulation on MWs affect the band structures in which the SWs are dispersed. The dispersion spectrum consists of allowed, and forbidden regions. The SWs are propagated in allowed regions and prohibited in forbidden regions by tuning the band structures in periodic magnetic materials that offer new functionalities in the data processing, and transmission technology [22-25]. In microwave communication, the waveguides have been extensively used to carry high frequencies with low power attenuation which are in the hollow tube structures [26]. Though the advancements in modern electronics the waveguides provide an efficient and excellent role in microwave communication, it confronts limitations like size and operation of frequency. The inherent fundamental limitations in electronics-based waveguides are heat dissipation due to electrons moving in the semiconductor [27-28]. In addition, scaling law (Moore’s law) also reached its limit, further reducing length it causes the high leakage current in the devices which in turns the more power dissipation [29-30]. The scientific community’s challenges to over limitations in scalability and power dissipation in the devices have increased in recent years [31]. In the quest to overcome those limitations, the magnonics deals the

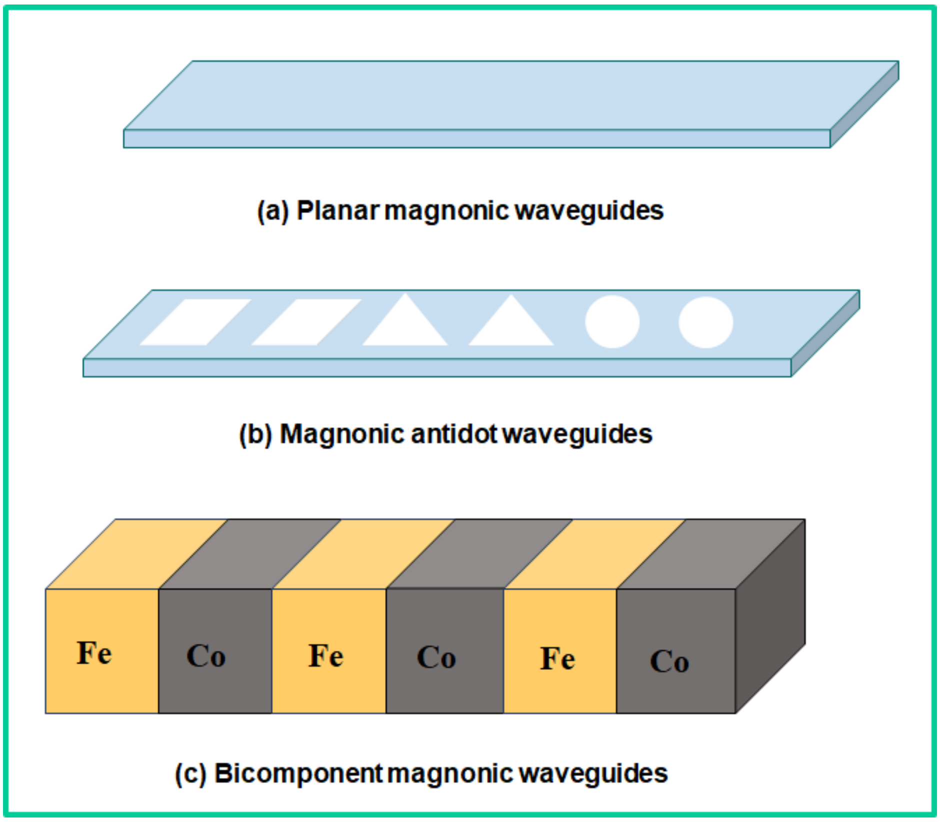

Figure 4: The various types of MWs. (a) Planar Magnonic Waveguide made up of permalloy material (b) MAWs have different shapes and sizes of antidots on Permalloy MWs (c) Bicomponent magnonic waveguides comprises of different constituent magnetic properties lead to design long distance communication devices.

directional property of spins whose wavelength is shorter than the electromagnetic waves in the frequency range (GHz to THz) due to dipolar and exchange spin-interactions [32-33]. Hence, magnonics has several advantages by including easier integrability and compatibility with CMOS structure, programmability, negative group velocity, non-reciprocity, smaller device features, efficient tunability, and lower energy consumption [34-35]. The outbreak of research on magnonics has been devoting its excellence in many branches, as shown in Fig. 5.

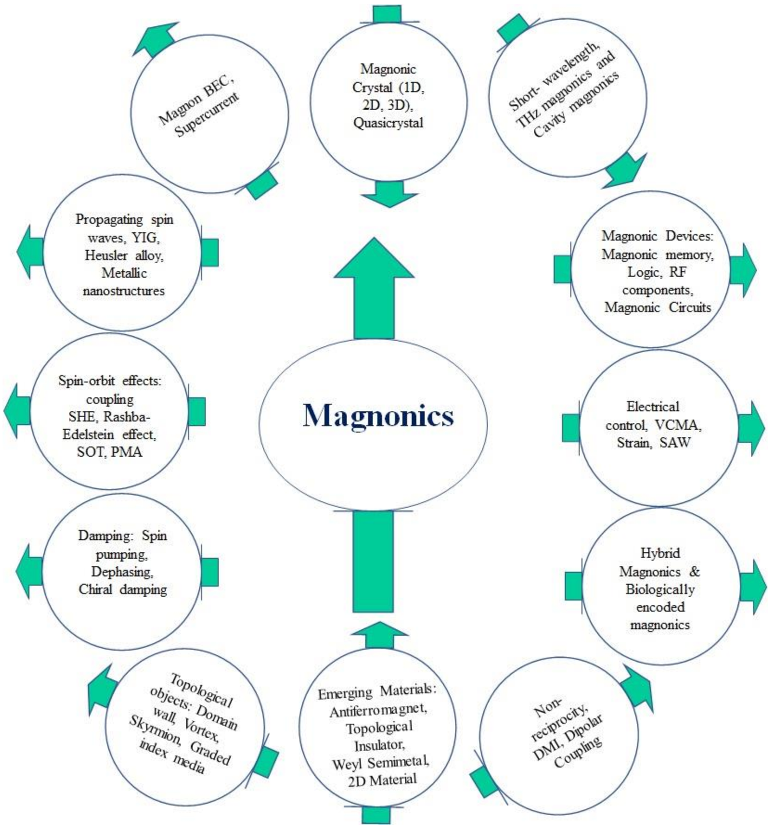

Figure 5: Diverse fields have been covered by the magnonics.

In recent years, the scientific community have shown keen interest to study the SW propagation in nano-structured magnetic materials and controlling of information carried by them. The reliability of regulating the SWs in ordered magnetic materials has utter attention in information transmission and processing devices, such as logic circuits, logic gates, frequency selective magnonic drop filters, magnonic filters, non-linear magnonics circuits, SW demultiplexers, power splitters, and microwave couplers [36-38]. Moreover, engineering the SWs in GHz to THz range covers a wide range of fields like magnon-spintronics, multiferroic magnonics, magnonics-semiconductor, and magnon straintronics etc [39-40]. Many works have been done on width modulated planar MWs by changing the sizes of widths, pitch, and lattice constant to steer the propagation of SWs in specific frequencies range (filtering properties). For example, Fig. 6 (a) shows the dispersion spectrum of planar MW (made up of permalloy) exhibited the continuous frequency range from 20 to 150 GHz [41], which is not suitable for filtering properties. In order to get filtering properties, the triangular antidots are incorporated with different orientations such as ($\theta = 0^0$, 45^0, and 90^0) as shown in Fig 6(b-d). Due to different orientations of triangular antidots affect the symmetry breaking in the width direction, reducing the number of forbidden bands and their width, highly suitable for filtering applications. Hence, MAWs are the promising candidates to design the SW-based filtering devices. However, recently, some researches have shown a keen interest in periodic arrangement of nano-stripes with alternating magnetic materials-based waveguide known as BMW which have a capacity to design the information transmission and processing devices in the nano-scale.

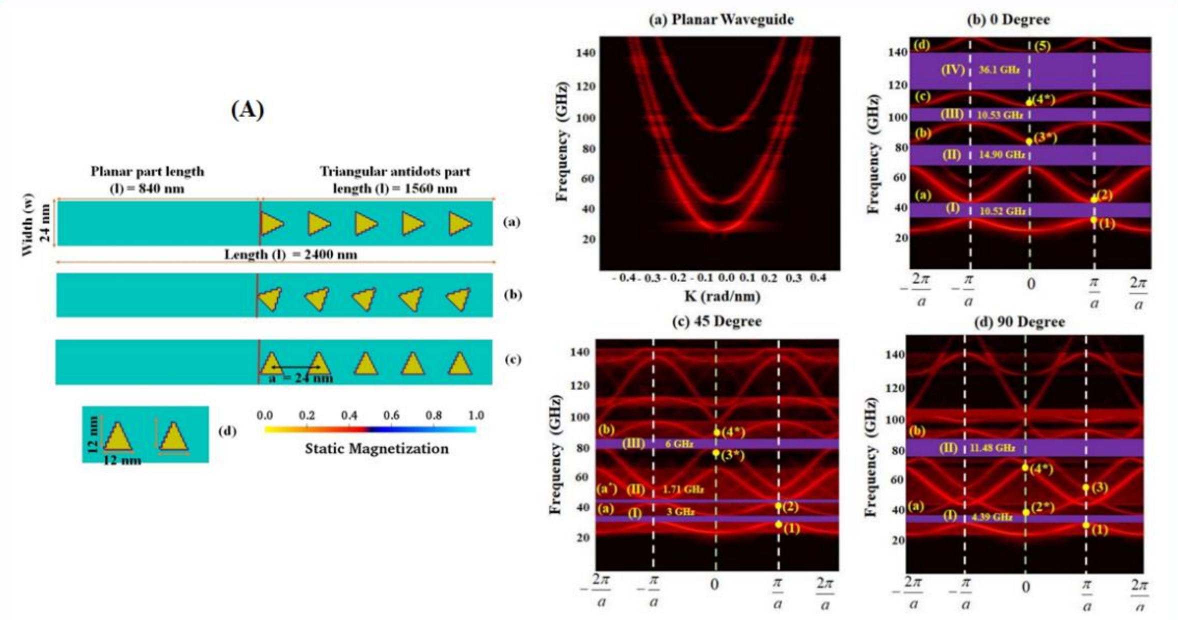

Figure 6: (A) The schematic view of MAWs, composed of planar region (upto 840 nm) and triangular-shaped antidots region (840 nm to 2400 nm). (a) The dispersion characteristics are computed for the planar waveguide whose length from 1 to 840 nm as shown in Fig. 1(a). (b)–(d) MAWs with various orientations ($\theta = 0^0$–90^0) from length = 840 to 2400 nm with 45^0 increments. Purple region: Forbidden bands and its numerical value of the gap width. Dotted lines: BZ boundaries.

BMWs have able to achieve the high group velocity and wide transmission bands due to contrast in magnetic materials highly suitable for an efficient signal processing devices such as short- and long-range communications. In this work [42], the BMWs devised which is composed of alternating SM and N stripes periodically as shown in Fig. 7 (A). BMWs exhibit wide transmission bands ≈ 14 -60 GHz and high group velocity ≈ 8500 - 10600 m/s due to increasing exchange coupling at the interfaces of two constituents' magnetic materials help to transmit the information throughout the entire waveguides. The tunability of high group velocity and wide transmission bands in BMWs depending on periodicity and present of saturation magnetization of materials. The designed MWs in this work are suitable for constructing effective signal processing devices at a nano-scale regime.

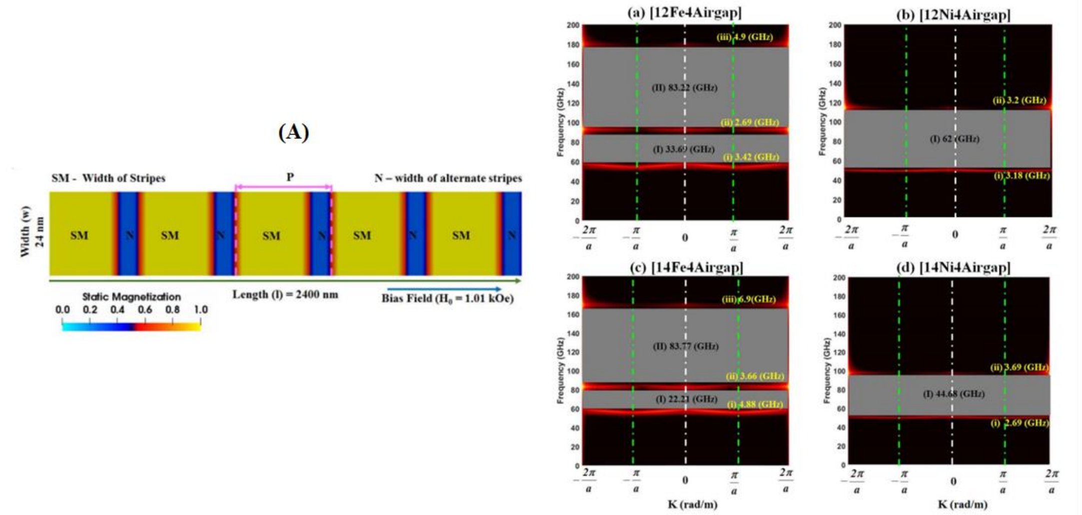

Figure 7: (A) Schematic view of BMWs with length = 2400 nm, width = 24 nm, and thickness = 3 nm. The SM and N indicate the widths of their respective stripes which determines the periodicity P = SM + N of the waveguide.

MAWs are promising candidates for deliberating the filtering properties, which are suitable for communication channel purposes. Many research groups have been engaged their works to obtain the filtering properties by establishing the different MAWs. Based on this notion, the cascaded magnonic waveguide (CMAW-See Fig. 8) devised to obtain the desired channel width by tuning the band structures of the waveguide [43]. The CMAWs composed of two regions based on channel width (CWs). **Region (I):** Embedded by the equal sides of antidots (Square) exhibits the two allowed frequencies (AFs) within the range of 80 to 150 GHz and Region (II): Embedded by length *l* modulation on alternate antidots, maintains constant CW, and the width *w* modulation on alternate antidots varied the CW. In each waveguide the Region (I) and Region (II) are cascaded at the center of the waveguide. The SW propagation in Region (II) where *s* modulation done (Constant CW) exhibits three AFs, by opening of the bandgap. The tail like-structure distribution of the exchange fields on alternate antidots regions produces an additional

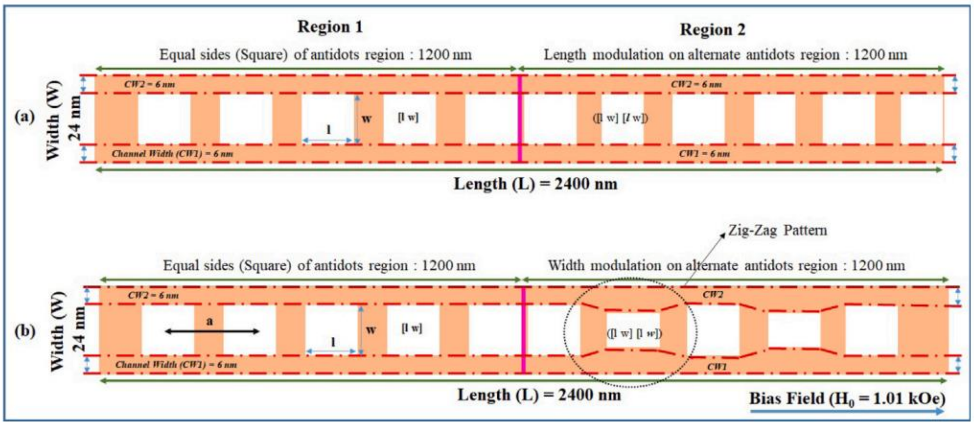

Figure 8: The pictorial representation of MAWs with square shaped antidots cascaded with l and w modulation of alternate antidots along the length=2400 nm, width= 24 nm and thickness = 3 nm. The equal side of antidot (squared-shaped) region and the length l, width w modulation on alternate antidots are denoted as [l w] and ([l w] [l w]) along with the constant periodicity indicated by a = 24 nm respectively.

AF and influences the group velocity v_g of respective AFs, ranging from 397 to 519 m/s. The tunability of CW is possible by varying the width w of alternate antidots that generate the demagnetization field asymmetrically in Region (II), and drastically reduce the vg within the range of ≈128 to 460 m/s. The proposed work to construct the magnonic waveguides adjacent to steers the SW propagation in different selective frequencies, suitable for multiplexing/demultiplexing with desired CWs.

Magnonic Nano Devices

The utilizing of MWs to construct the magnonic devices has paved the way to design the low-loss nano-sized processing devices for the next generation in microwave communication. In this respect, the waveguide with controllable bandgaps would have fascinated applications in microwave systems such as transistors, feedback loops, logic gates, filters, etc. The MWs act as the stopband and passband filters.

A. V. Chumak et al. [44], experimentally studied the SWs propagation in 1- D MWs, which consists of grooved pattern regions on Yttrium Iron Garnet film (YIG). The grooved pattern was made in YIG MWs using the photolithographic technique, acts as stopband filters where the SW propagation can be prohibited. The rejection bands are observed in MWs strongly depend on the grooves’ depth. Increasing the groove depth shows an increase in the frequency width and rejection efficiency of the rejection bands. The number and width of grooves also played to control the rejection efficiency in YIG MWs, which effectively provide the function of stopband filters.

Qi Wang et al. [45] designed the reconfigurable MWs using voltage-controlled perpendicular magnetic anisotropy (PMA) in ferromagnetic dielectric heterostructures. The periodic manner of the gate metallic stripes on the MgO/Co structures in substrates, where the electric field is applied, modifies the PMA in Co. The pronounced bandgaps in SW spectra are obtained due to the voltage-controlled PMA that induces the spatial variation of the internal field in the waveguides. The switch ON and OFF of the pronounced bandgaps within a few tens of nanoseconds is possible. Further, the applied voltage is used to tune the width and center frequencies of the bandgaps. Applying the various voltage in the different metallic gates controls the bandgaps that resemble the reconfiguration function. The proposed voltage-controlled reconfigurable MW makes the paths to design the nanosized magnon spintronics devices with low power consumption.

In this regard, A.V. Chumak [46], and his group designed the magnon transistors by controlling the source to drain current due to the magnons' injection in the transistors' gate. The non-linear four magnon scattering process is responsible for the operational principle of the transistor, which is enhanced by the MWs that have high magnon densities at the gate. The designing of logic gates can be done directly using the magnon circuits, enabling the coding of signals in magnon density that can be amplified.

For instance, the XNOR logic gate was done using magnon transistors embedded into two arms using the principle of Mach-Zender interferometer. The CMOS XOR logic gates require a minimum of eight field-effect transistors, but the single-chip XOR logic gates consist of two transistors. In the future particle-less technology, the information will be carried and processed by magnons rather than by electrons.

The magnonic nanochannels (MNCs) were developed in [47] by periodically tailoring perpendicular magnetic anisotropy (CoFeB/MgO heterostructure) using the electric field. The voltage-controlled magnetic anisotropy (VCMA) can control the SWs in the magnonic band structure in this dynamic MNC by varying the applied gate voltage. Early, there is enhancement or decreases in the SW frequency in an unpatterned top gate electrode due to VCMA. The two frequency modes appear in magnonic band structures and reconfigurable bandgaps (BGs) in patterning a 1D array of ITO electrodes under the application of a modest electric field. Hence, the dynamic band structures and reconfigurable bandgaps are tuned in patterned and unpatterned electrodes in MNCs, unlocks access a way for developing the new genre of MNCs invoked by an energy-efficient stimulus, i.e., Spin-based magnonic nanocircuits can be devised with ultralow power consumption using the electric field as a significant key.

Many challenges and advantages have been met in recent decades by means of the advancement in nanofabrication technology with magnetism. Reasonably, the encoding of information signals as binary data by using the amplitude and phase of SWs is one of the strongest interesting attentions in the processing of digital data and computation. The first theoretical approach had done on the encoding binary data into the SWs' amplitude which is proposed by Hertal et al. [48] and also experimental was done in the same direction by Kostylev et al. [49]. The construction of SW-based logic gates was proposed using a Mach-Zender SW interferometer, which is equipped with current-controlled phase shifters embedded in the interferometer arms. The principle of XNOR and NAND gates was proved by using the above-mentioned idea [50].

To implement the SW-based logic devices and gates using the MWs, which poses different microwave applications and pave the ways for designing the microwave devices and components such as filters, transistors, phase-shifters, logic gates, etc. The MWs in which the SWs can steer the desired frequency operation that allows to design all SW circuitry using the magnonic gates and devices. Besides, the recent developments in advanced nanofabrication technologies, will help to manufacture the different types of nanoscale devices explored for the ultrafast information processing and ultrahigh density information storages around the world in future.

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