Topical Review

Spin wave propagation in uniform waveguide: effects, modulation and its application

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Abstract

Magnonics, or spin waves, are one of the most promising candidate technologies for information processing beyond complementary metal oxide semiconductors. Information encoded by spin waves, which uses the frequency, amplitude and/or phase to encode information, has a great many advantages such as extremely low energy loss and wideband frequency. Moreover, the nonlinear characteristics of spin waves can enhance the extra degrees of processing freedom for information. A typical spin wave device consists of a spin wave source (transmitter), spin wave waveguide and spin wave detector. The spin wave waveguide plays an important role of propagating and modulating the spin wave to fulfill the device’s function. This review provides a tutorial overview of the various effects of coherent spin wave propagation and recent research progress on a uniform spin wave waveguide. Furthermore, we summarize the methods of modulating propagation of a spin wave in a uniform waveguide, and analyze the experimental and calculated results of the spin wave propagation profile and dispersion curve under different modulation methods. This review may promote the development of information transmission technology based on spin waves.

Keywords: magnonics, spin wave devices, modulations of spin wave

(Some figures may appear in colour only in the online journal)

1. Introduction

Integrated circuits based on complementary metal oxide semiconductors (CMOSs) have achieved great success due to their high speed, low power consumption, and high scalability [1, 2]. However, integrated circuits based on CMOS technology are constrained by physical limits and power dissipation. Further reduction of channel length will result in more power consumption and introduce some quantum effects [3–8]. Among many CMOS candidate technologies, the information transmission method based on spin waves stands out due to its novel characteristics, high speed and extremely low power consumption [9].

Spin waves (magnonics) represent a phase-coherent collective oscillation of precessing magnetization vectors in a magnetic medium, first proposed by Bloch in 1930 [10]. From then on, spin waves have attracted increasing attention from researchers due to their novel characteristics. The most prominent advantage of utilizing spin waves for information
encoding is that the energy dissipation is extremely low due to the propagation of spin waves without Joule heating [11, 12]. Spin waves have a wide application band which covers the GHz band and even reaches the THz band. The minimum wavelength of spin waves can be as low as 10 nm, which is in line with the trend of miniaturization and integration of devices. In addition, information can be encoded into the amplitude and phase of spin waves, which makes the spin waves compute not only by Boolean logic but also by non-Boolean logic such as majority gates. Based on the above novel features, spin wave devices have become a promising competitor for beyond CMOS devices [12].

A typical spin wave device consists of three parts: a spin wave source (transmitter), spin wave waveguide and spin wave detector. According to different spin wave sources or excitation methods, spin waves can produce different degrees of coherence. The coherence of spin waves makes it possible to design spin wave devices based on wave interference. In this review, we specifically discuss coherent spin waves. As a key part of spin wave devices, the spin wave waveguide plays the role of propagating and modulating the spin wave. The propagation characteristics and phenomena of spin waves in different types of waveguides are different. Typical spin wave waveguides include uniform waveguides and magnonic crystals. Spin waves propagating in uniform waveguides and magnonic crystals show different propagation characteristics and phenomena. The special propagation characteristics and phenomena that exist during the propagation of spin waves also provide great convenience in the design of spin wave devices. Uniform waveguides generally refer to waveguides with uniform magnetization. The propagation of spin waves in uniform waveguides presents wave characteristics (e.g. dispersion, diffraction and interference) and geometric confinement effects (e.g. channelization and quantization) [13–21]. In contrast to uniform waveguides, magnonic crystals are artificially engineered crystals based on metamaterials. In magnonic crystals, spin wave propagation not only shows the wave characteristics but also exhibits the characteristics of spin wave forbidden bands [22–27]. In addition, researchers have also deeply studied the propagation characteristics of spin waves in finite-size nanometric magnetic elements such as magnetic dots or stripes [27–30]. When an external magnetic field magnetizes a nano magnetic element with finite size, the demagnetization effect causes a spin wave potential well to be generated inside, which makes the spin wave localized. This phenomenon can be explained by variational theory, which is consistent with the channelized phenomenon in a waveguide [27–34]. With these characteristics, functions such as spin wave beam splitting, self-focusing, frequency conversion, and wavelength conversion can be realized. These special propagation characteristics and phenomena make the design of spin wave devices more diverse and convenient. Thus, the study of propagation characteristics of spin waves in waveguides is key to the design of spin wave devices. In the last two decades, numerous spin wave devices have been implemented by simulation and experiment (e.g. phase shifters, logic gates, transistors, multiplexers) [35–53]. However, most spin wave devices still have the problems of poor power consumption and efficiency. Solving these problems is key to the development of spin wave devices.

The main goal of this review is to provide an introduction to spin wave theory and the challenges in spin wave device design based on a uniform waveguide. This review starts with an introduction to spin wave propagation characteristics in a uniform waveguide (section 2). Subsequently, we combine the contents of section 2 to introduce modulation methods of spin waves (section 3). Finally, section 4 concludes the review with an overview of the research on spin wave modulation technology and points out the challenges in implementing and designing high-efficiency spin wave devices.

2. Effects of spin wave propagation in uniform waveguides

This section provides an introduction to spin wave propagation characteristics. We start by explaining the dispersion relation of spin waves, followed by introducing some important phenomena of spin wave propagation.

2.1. Dispersion relations in uniform waveguide

The dispersion relation of a spin wave in a uniform waveguide is complex. It is mainly related to the following factors: the direction and size of the wavevector, the relative magnitudes of the exchange interaction and dipole interaction, the shape of the waveguide, the amplitude of the applied magnetic field, and the direction of the applied magnetic field relative to the propagation direction of the spin wave [13]. Moreover, magneto-crystalline anisotropy and magnetostriction can also affect the dispersion relationship.

For a uniform waveguide of width $w$ and thickness $d$, the total wavevector $k$ is shown below:

$$k = \sqrt{k_\perp^2 + k_\parallel^2}$$

(1)

where $k_\perp$ and $k_\parallel$ are the components of the wavevector along the length and width of the waveguide, respectively. Due to the size limitation of the waveguide width, $k_\perp$ is expressed as:

$$k_\perp = \frac{n\pi}{w} \quad (n = 1, 2, 3 \ldots).$$

(2)

The azimuth of the wavevector $\theta_k$ is the angle between the wavevector and the long axis of the waveguide, which can be expressed as:

$$\theta_k = \arctan\left(\frac{k_\perp}{k_\parallel}\right) = \arctan\left(\frac{n\pi}{k_\parallel w}\right).$$

(3)

By combining the above equations and simplifying the wavevector $k = k_\parallel$, the dispersion relation can be expressed as follows:
the waveguide with \( w \) the waveguide. When magnetizing along the waveguide axis, the magnetizing state can be described with the effective width \( w_{\text{eff}} \). The pinning condition is given by equation (4) with \( w_{\text{eff}} \approx 1 \). In equation (4) does not consider the effects of spin pinning on the waveguide surface, high-order thickness modes, or magnetocrystalline anisotropy.

The demagnetization factor and the spin pinning condition at the edge of the waveguide need to be considered when the width of the spin wave waveguide reaches the micrometer level or less. Due to the large length of the waveguide, the demagnetization factor in the length direction can be ignored when the waveguide is magnetized along the long axis, \( \theta_M = 0 \), i.e. \( k \parallel M (M \text{ is the magnetization vector}) \). In this configuration, the effective field \( H_{\text{eff}} \) in the waveguide is equal to the applied magnetic field \( H_0 \). The spin pinning condition is mainly determined by the dipole field, and the spin at the edge of the waveguide is usually in a partially pinned state. The pinning state can be described with the effective width \( w_{\text{eff}} \). There are different ways to define the effective width. The most common definition is the distance between two points corresponding to 10% of the maximum effective field at the center of the waveguide. When magnetizing along the waveguide axis, \( w_{\text{eff}} \geq w \), there are the following situations: \( w_{\text{eff}} > w \) represents complete pinning, \( w_{\text{eff}} > w \) represents partial pinning, and \( w_{\text{eff}} \rightarrow \infty \) represents no pinning at all. The effective width of the waveguide with \( \theta_M = 0 \) is shown as:

\[
\omega(k) = \sqrt{\left(\omega_0 + \omega_m \lambda_{\text{ex}} \left[k^2 + \left(\frac{n \pi}{w}\right)^2\right]\right)} \left(\omega_0 + \omega_m \lambda_{\text{ex}} \left[k^2 + \left(\frac{n \pi}{w}\right)^2\right] + \omega_m F\right)
\]

(4)

\[
F = 1 - g \cos^2(\theta_k - \theta_M) + \frac{\omega_0 g (1 - g) \sin^2(\theta_k - \theta_M)}{\omega_0 + \omega_m \lambda_{\text{ex}} \left[k^2 + \left(\frac{n \pi}{w}\right)^2\right]}
\]

(5)

\[
g = 1 - \frac{1 - \exp\left(-d\sqrt{k^2 + \left(\frac{n \pi}{w}\right)^2}\right)}{d\sqrt{k^2 + \left(\frac{n \pi}{w}\right)^2}}
\]

(6)

where \( \omega_0 = \gamma_0 \mu_0 H_{\text{eff}} \) (\( H_{\text{eff}} \) is the effective field in the waveguide, \( \mu_0 \) is the vacuum permeability constant and \( \gamma_0 \) is the gyromagnetic ratio), \( \omega_m = \gamma_0 \mu_0 M_s \) (\( M_s \) is the saturation magnetization), \( \lambda_{\text{ex}} = 2 \frac{4\pi}{\mu_0 M_s} \) (\( \lambda_{\text{ex}} \) is the exchange constant of the waveguide) and \( \theta_M \) is the angle between the magnetization direction (or direction of applied magnetic field) and the long axis of the waveguide. It should be noted that, in theory, equation (4) is tenable only when the waveguide width is wide and \( kd \gg 1 \). In addition, equation (4) does not consider the effects of spin pinning on the waveguide surface, high-order thickness modes, or magnetocrystalline anisotropy.

1. \( \theta_M = \frac{\pi}{2} \) means that the magnetization direction of the waveguide is along the tangential direction. The applied magnetic field competes with the shape anisotropy equivalent field. At this time, the magnetization tends to align along the long axis of the waveguide, thereby minimizing the static stray field. Obviously, the effective field (internal magnetic field) acting on the waveguide at this time is smaller than the external field and presents a non-uniform distribution; that is, the effective field at the edge of the waveguide is the smallest, and the effective field at the center of the waveguide is the largest.

Assuming that the direction of magnetization in the waveguide is always along the width of the waveguide, the effective field is expressed as:

\[
\mu_0 H_{\text{eff}} = \mu_0 H_0 - \frac{\mu_0 M_s}{\pi} \left[\tan\left(\frac{d}{2z + w}\right) - \tan\left(\frac{d}{2z - w}\right)\right]
\]

(8)

where \( w \) and \( d \) are the width and thickness of the waveguide, respectively. \( z \) is the coordinate along the tangential direction of the waveguide and \( -w/2 \leq z \leq w/2 \). Usually, spin waves can be propagated either along the central area (central mode) of the waveguide or along the edges (edge mode) of the waveguide. For the central mode, the effective field of the waveguide is considered to be uniform, and its maximum value is given by equation (8) with \( z = 0 \). Obviously, for the case where the magnetization direction is along the tangential direction of the waveguide, the effective width of the waveguide satisfies \( w_{\text{eff}} < w \).

Figure 1 shows the dispersion relationship of a uniform Yttrium Iron Garnet (YIG) waveguide and YIG film [13]. The width and thickness are \( w = 1 \mu m \) (waveguide), \( w = \infty \mu m \) (film), and \( d = 100 nm \), respectively. The saturation magnetization and exchange constant are \( M_s = 140 kA/m \) and \( A_{\text{ex}} = 3.5 \text{ pJ/m}^{-1} \), respectively. The applied magnetic field \( \mu_0 H_0 = 100 \text{ mT} \) is parallel to the waveguide or film plane. Whether in magnetic films or waveguides, the dispersion relation of spin waves can be divided into three regions: magnetostatic waves with small wavenumber, exchange waves with large wavenumber, and dipolar-exchange spin waves (DESWs) for which the wavenumber is between the first two. For spin waves of \( \theta_M = 0 \) and \( \theta_M = \frac{\pi}{2} \) in magnetic films, the frequencies are ferromagnetic resonance frequencies (the corresponding frequency in figure 1 is 4.65 GHz) of magnetic films with \( k = 0 \). However, it is completely different for uniform waveguides. \( k_\perp > 0 \) always holds in uniform waveguides. For the spin waves of \( \theta_M = 0 \) (\( n = 1 \), calculation from equation (7) shows that \( w_{\text{eff}} \approx 1.22 \mu m \), then \( k_\perp = \frac{\pi}{w_{\text{eff}}} = 2.58 \text{ rad} \mu m^{-1} \). Thus, its...
The effective field distribution in this direction is shown in figure 2(b). A spin wave potential well is formed at the edge of the waveguide. Furthermore, the lowest cutoff frequency distribution of the spin wave along the width of the waveguide is calculated according to the dispersion relation, as shown in figure 2(c). It can be seen from figure 2 that the spin wave beam can be distributed over the entire waveguide width with excitation frequency $f > 10$ GHz. The spin wave beam can only be distributed at the edge of the waveguide with excitation frequency $f < 10$ GHz which leads to the phenomenon of channelized spin wave propagation.

### 2.2. Quantization phenomenon

For magnets of limited size, wavevectors of spin waves may be discretized or quantized in the direction of limited size. Perpendicular standing spin waves formed in the thickness direction of the magnetic film are a typical case. However, the dimensions in both the thickness direction and the width direction are limited in uniform strip waveguides. The quantization phenomenon model of spin waves is shown in figure 3. Considering the limited size in the width direction, the wavevector $k_w$ in this direction has the following equation:

$$k_w = \frac{n\pi}{w_{\text{eff}}}, \quad (n = 1, 2, 3, \ldots). \quad (9)$$

The spin wave propagation diagram in the uniform spin wave waveguide was probed using μBLS spectroscopy, and the experimental results showed an obvious quantization phenomenon [15]. Figure 4 shows the experimental results of a waveguide with a width of 1 μm and thickness of 20 μm. This experiment studies the DESW. The dotted line in figure 4 is the theoretical calculation curve of the dispersion relation of a large film of the same thickness. The horizontal solid line is the curve calculated using equation (10) and taking $k_f$ as the discrete value. $H$ is the applied magnetic field and $d$ is the thickness of the waveguide:

$$\omega_{\text{DE}} = \frac{\gamma_0}{2\pi} \left( H + 4\pi M_s \right) + \left( 2\pi M_s \right)^2 \left( 1 - e^{-2kd} \right)^{1/2}. \quad (10)$$

### 2.2.1. Channelized phenomenon

For a spin wave propagating in a uniformly magnetized waveguide, depending on the propagation frequency, the spin wave beam can be concentrated in the middle of the waveguide or it can be split into two beams to propagate at the edge of the waveguide, as shown in figure 2(d). The above phenomenon is named channelized spin wave propagation.

This phenomenon can be explained by the demagnetizing effect in the width direction of waveguides [14]. In this experiment, the waveguide is composed of a permalloy (Py) strip with a thickness of 20 nm and width of 2.1 μm. A bias magnetic field with $H_0 = 0.11$ T is applied along the direction perpendicular to the long axis of the waveguide. The Damon–Eshbach (DE) mode spin wave is excited by a 1 μm wide microstrip antenna, and the propagation of the spin wave is probed by micro-focus Brillouin light scattering (μBLS) spectroscopy, as shown in figure 2(a). Although the applied magnetic field applied along the direction perpendicular to the long axis of the waveguide is uniform, a demagnetization field is still generated in this direction due to the size limitation. The effective field distribution in this direction is shown in figure 2(b) after considering the demagnetizing field. The effective field at the edge is significantly smaller than that at the center, as can be seen from figure 2(b). A spin wave potential well is formed at the edge of the waveguide. Furthermore, the lowest cutoff frequency distribution of the spin wave along the width of the waveguide is calculated according to the dispersion relation, as shown in figure 2(c). It can be seen from figure 2 that the spin wave beam can be distributed over the entire waveguide width with excitation frequency $f > 10$ GHz. The spin wave beam can only be distributed at the edge of the waveguide with excitation frequency $f < 10$ GHz which leads to the phenomenon of channelized spin wave propagation.

### 2.2.2. Self-focusing phenomenon

Demidov et al. utilized μBLS spectroscopy to explore the propagation characteristics of DESW in uniform waveguides [16, 17]. They found that the spin wave propagates unevenly along the waveguide and has a complex relationship with the spatial coordinates. For the region near the excitation antenna, the spatial distribution of the spin wave beam is wider, and there are two maximum peaks at the edge of the region and a minimum peak at the center of the region. For the region far away from the excitation antenna, the tangential distribution of the spin wave beam changes, a maximum peak appears in the center of the strip, and the beam width decreases, as shown in figure 5.

The self-focusing phenomenon can be explained by the interference effect between the quantized modes in the width direction of the spin wave in uniform waveguides. As mentioned in the previous section, the wavevector component parallel to the width of the strip is quantized, while the wavevector...
component along the long axis of the strip is continuous. This quantization phenomenon makes the dispersion curve of DESW split into a cluster of curves, because the wave has different antinodes along the width, as shown in figure 6(d). At a specific excitation frequency, the spin waves of multiple modes in the waveguide are excited at the same time. It should be noted that the even-order mode cannot be excited, only the odd-numbered mode can be excited, and the excitation efficiency is proportional to $1/n^2$ due to the uniformity of the magnetic field excited by the antenna microwave. Thus, the mode analysis for $n > 5$ can be ignored; that is, only the relationship between the $n = 1$ and $n = 3$ modes is considered. Figures 6(a) and (b) are the propagation diagrams of the spin wave modes with $n = 1$ and $n = 3$ when there is no interference effect.
respectively. Due to the difference in phase velocity between different modes, spin waves of two modes with the same frequency will interfere when propagating along the waveguide axis at the same time. The interference period is \( l = \frac{2\pi}{\Delta k} \).

The dynamic magnetization component of the \( n \)-order mode is as follows:

\[
m_n(y,z) \propto \sin \left( \frac{n\pi y}{w} \right) \cos (k_n^z z - \omega t + \varphi_n),
\]

where \( k_n^z \) is the longitudinal component of the \( n \)-order spin wave mode wavenumber, \( \omega = 2\pi f \) is the cyclic excitation frequency, \( w \) is the waveguide width and \( \varphi_n \) is the phase of the excitation source. The intensity distribution of the spin wave is proportional to the average value of \( m_n(y,z) \) in the oscillation period \( 2\pi/\omega \). It can be seen from equation (11) that the spin wave intensity is also periodically distributed along the propagation direction at a specific time point. \( k_n^z \) of spin waves in different modes is different. Therefore, the periodicity of

Figure 5. Schematic of the self-focusing phenomenon of the spin wave in a uniform waveguide. Reprinted (figure) with permission from [17], Copyright (2008) by the American Physical Society.

Figure 6. Schematic of the propagation of spin waves with different modes (a) \( n = 1 \), (b) \( n = 3 \), (c) \( n = 1 \) and \( n = 3 \), (d) Dispersion relationship of waveguide width quantization mode. Reprinted (figure) with permission from [17], Copyright (2008) by the American Physical Society.
spin wave intensity distribution along the propagation direction is different in different modes. Due to the different periodicity, the distribution of the spin wave intensity diagram after \( n = 1 \) and \( n = 3 \) mode spin wave interference in the propagation direction is not uniform but presents the phenomenon of self-focusing. In the process of calculating the interference image, utilizing \( m_1(y,z) + \frac{1}{3}m_3(y,z) \) (the excitation efficiency of spin wave modes of different orders is considered here), the total spin wave intensity is

\[
I_{\Sigma}(y,z) \propto \sin\left(\frac{\pi w}{w_1} y\right)^2 + \frac{1}{9} \sin\left(\frac{3\pi w}{w_1} y\right)^2 + \frac{2}{3} \sin\left(\frac{\pi w}{w_1} y\right) \times \sin\left(\frac{3\pi w}{w_1} y\right) \cos(\Delta k_z z + \Delta \varphi) \tag{12}
\]

where \( \Delta k_z = k_3^z - k_1^z \) and \( \Delta \varphi = \varphi_3 - \varphi_1 \). It can be seen from equation (12) that the interference between spin waves of different modes is periodic, and the period is \( l = \frac{2\pi}{3\pi} \). The relative phase shift between different modes is represented by \( \Delta \varphi \). Figure 6(c) shows the intensity of the interference spin wave, from which it can be seen that equation (12) is in good agreement with the experimental results. It can be seen from the above equation that a narrower width of the stripe will lead to more obvious separation of the dispersion curve caused by the transverse quantization of spin waves, and a smaller interference period. It should be noted that equations (11) and (12) are obtained when the magnetic moment at the waveguide edge is fully pinned. For waveguides with smaller width, the effective width should be considered.

2.2.4. Nonlinear self-modulation effect of spin wave beam width. At present, most designs of spin wave devices are based on the linear approximation of spin waves; that is, the spin precession angle is relatively small. However, the existence of a large number of nonlinear phenomena is also one of the important characteristics of spin waves. Demidov et al utilized space- and time-resolved microfocus BLS spectroscopy to study the propagation characteristics of spin waves in Py stripes with 2.4 \( \mu \)m width and 36 nm thickness [18]. In this experiment, as a spin wave source, the microwave antenna has an excitation power range of 1–400 W. Figure 7 is the propagation diagram of the spin wave under different excitation powers; the excitation frequency is \( f = 8.8 \) GHz, and the applied magnetic field is \( H_0 = 830 \) Oe. It can be seen from figure 7 that the beam width of the spin wave changes nonlinearly with the increase in excitation power. This change is named transverse self-modulation. This self-modulation phenomenon only occurs under nonlinear conditions. The spin wave is transmitted linearly in the waveguide with excitation power \( P = 10 \) mW, and the energy of the spin wave is periodically concentrated in the middle of the waveguide (this feature can be explained by the self-focusing effect in the previous section). In this case, the width of the spin wave beam only slightly changes; that is, there is no significant difference in the beam width between the focused and the unfocused regions, as shown in figure 7(a). With the increase in the excitation power, the beam in the focused region is compressed nonlinearly, while the beam in the unfocused region is nonlinearly broadened. This makes the phenomenon of nonlinear self-modulation of spin wave beam width significant.

This abnormal nonlinear phenomenon is the result of competition between the nonlinear frequency shift of various width modes of the spin wave and the nonlinear damping caused by four magnon scattering. The change of damping affects the amplitude of the spin wave. Obviously, the increase in damping increases the decay rate of the spin wave. Figure 8 shows the relationship between the nonlinear self-modulation
effect and nonlinear damping. The self-modulation depth can be defined as:

$$\frac{\delta w}{w} = \frac{2(w_{\text{max}} - w_{\text{min}})}{(w_{\text{max}} + w_{\text{min}})}$$

(13)

$P_{\text{th}}$ is the threshold power required for self-modulation and nonlinear damping phenomena. Compared with figures 7(b) and 8, it is found that the self-modulation depth increases with an increase in the decay rate of the spin wave, and the self-modulation depth has the same threshold power as the decay rate of the spin wave (here 50 mW). The self-modulation phenomenon is closely related to nonlinear damping, and Demidov et al also revealed this through time-scale experimental data.

2.2.5. Tunneling effect. In quantum mechanics, the tunneling effect refers to the quantum behavior in which microscopic particles such as electrons can enter or pass through high potential barriers (the height of the potential barriers is greater than the total energy of the particles). It is a manifestation of the volatility of quantum mechanics particles. In 1928, George Gamow proposed to use the tunneling effect to explain the alpha decay of atomic nuclei. A spin wave originates from the inherent spin of the particle. Thus, the tunneling effect can also occur in the propagation of spin waves.

The potential barrier in a uniform spin wave waveguide is composed of magnetic inhomogeneity micro-regions. These magnetic inhomogeneity micro-regions can be realized in many ways, such as being formed in the propagation direction of the waveguide by utilizing an energized conductor or generated in the region where the saturation magnetization changes. In the 1960s, the propagation of spin waves in a non-uniform magnetic field was studied. Schlömann first noticed the similarity between the propagation of exchange mode spin waves and the motion of quantum mechanical particles [19]. Under the condition of ignoring the magnetic dipole exchange effect and magnetic anisotropy, the LLG equation describing the dynamic characteristics of magnetization can be rewritten as the static Schrödinger equation, where $m \propto \exp(\ii \omega t)$ is similar to the wave function, and the magnetic field is used as potential energy; then [20]:

$$-\frac{2A}{M_s} \frac{\partial^2 m}{\partial z^2} + \left[H(z) - \frac{\omega}{\gamma}\right] m = 0,$$

(14)

where $m$ is the magnetization, $A$ is the exchange stiffness, $M_s$ is the saturation magnetization, $\gamma$ is the gyromagnetic ratio, $z$ is the direction of spin wave propagation and $H(z)$ is the applied magnetic field component in the $z$ direction. From equation (14), it can be concluded that the dispersion relation of a plane spin wave ($m \propto \exp(\ii k z)$) is as follows:

$$\omega = \Delta(z) + \frac{2\gamma A k^2}{M_s}$$

(15)

where $\Delta(z) = \gamma H(z)$ is the band gap of the dispersion spectrum, which is very similar to the dispersion of microscopic particles in the potential field $U(z)$:

$$E = U(z) + \frac{k^2}{2m}.$$

(16)

It is assumed that the spin wave with frequency $\omega$ enters the inhomogeneous magnetic region $H = H(z)$ and the band gap $\Delta(z) = \gamma H(z)$ is appropriate. In this case, by changing the wavevector of the spin wave in the region $k = k(z)$, the dispersion relation of equation (15) can be established, and the spin wave can tunnel through the region. However, if the difference between the band gap and $\omega$ is too large, there will be no wavevector satisfying the dispersion relation at this frequency, so the spin wave will be reflected in this region. Therefore, in this case, the region becomes a potential barrier that hinders the propagation of spin waves.

Spin waves can tunnel through the magnetic inhomogeneous micro-region via the exchange effect, when the size of the magnetic inhomogeneous region is close to the exchange length. Under the condition that the size of the magnetic inhomogeneous region is much larger than the exchange length, if the wavelength of the spin wave is greater than the width of the magnetic non-uniform region, the spin wave can tunnel through this region by dipole–dipole interaction. In 2010, Schneider et al utilized $\mu$BLS spectroscopy to observe the phenomenon of spin waves tunneling through the magnetic
inhomogeneous region via the dipole–dipole interaction [21]. As shown in figure 9, the backward volume magnetostatic spin wave (BVMSW) configuration is used in the experiment, and the magnetic inhomogeneity region is composed of an air gap with a width of 38 µm (represented by black lines in figure 9). Spin waves are excited at the left end of the waveguide; the excitation frequency is 7.132 GHz and the pulse width is 200 ns. It can be seen from figure 9 that most of the spin waves are reflected in the air gap, and standing waves are formed on the left side of the air gap. However, a small portion of the spin waves tunnel through the air gap. Furthermore, it can be seen that tunneling is more likely to occur when the applied magnetic field decreases.

3. Modulations of spin wave propagation characteristics in uniform waveguides

The heart of a spin wave device is a waveguide that transmits and processes spin waves. The dispersion characteristics of a spin wave depend on the effective field in the waveguide. Both the structure of the waveguide and the internal micromagnetic structure affect that. In addition, the effective field is also related to the dipole field between the materials and external field. This section describes some typical methods of modulating spin wave propagation characteristics in uniform waveguides. We introduce it from three aspects: structure modulation, external field modulation and dipole field modulation.

3.1 Structure modulation methods

As described in equation (4) in section 2, the dispersion relationship of spin waves is closely related to the effective field of the waveguide. The effective field in the waveguide can be changed by changing the microstructure or forming topological magnetic structures. This section describes the above two aspects with examples.

3.1.1 Microstructure modulation methods. There are many ways to change the structures of magnetic media, such as changing the width of the magnetic media and setting defects. Compared with other modulation methods, this type of modulation method is more direct and stable.

Demidov et al proposed a variable-width waveguide structure, as shown in figure 10(a) [38]. DE mode configuration was adopted in this experiment. As mentioned in section 2, the phenomenon of channelized spin wave propagation occurs due to the existence of a spin wave potential well in uniform waveguides. The spin wave potential well is closely related to the demagnetization effect in uniform waveguides, and the demagnetization effect is different in different width waveguides. As shown in figure 10(b), the internal magnetic field in the wider waveguide is more uniform, while there is obvious inhomogeneity in the narrower waveguide. The difference in the internal magnetic field distribution makes the dispersion curve different. Figure 10(c) depicts the dispersion curves in the wider and narrower waveguides. The dispersion curve in the narrower waveguide shifts down by about 0.5 GHz compared to that in the wider waveguide. This shift causes the special propagation phenomenon of spin waves shown in figure 10(d). Figure 10(d) shows that as the width of the waveguide increases, the spin wave propagating in the wider part of the waveguide exhibits the phenomenon of channelization. Utilizing this kind of waveguide structure, the mode conversion of spin waves can be realized effectively (unchannelized transmission to channelized transmission). This type of waveguide structure can be used for spin wave interference to design spin wave logic devices. For example, we can build a narrow–wide–narrow waveguide and change the phase of the spin wave on one side of the wide waveguide.
in other ways, thus forming the function of the spin wave inverter.

Introducing defects into a spin wave guide is also one of the classical methods to modulate a spin wave. Daniel et al. studied the diffraction of spin waves propagating in a Py waveguide with a submicrometer-sized circular defect [39]. In this experiment, the transmission characteristics of DESW are studied. The existence of defects leads to local inhomogeneity of the

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**Figure 10.** (a) Diagram of the experiment. (b) Distribution of the internal magnetic field in the waveguide. (c) Dispersion curves at the wider and narrower waveguides. (d) Diagram of intensity distribution of spin waves at different excitation frequencies. Reprinted (figure) with permission from [38], Copyright (2009) by the American Physical Society.
first specifying the function of the spin wave device, and then inversely designing spin wave devices by using defects, that is, in his published papers any logic function. Recently, Qi Wang confirmed this view of spin wave devices can build spin wave logic devices with spin wave. In theory, reasonable use of defects in the design from figure propagation characteristics of the spin wave. It can be seen internal magnetic field of the waveguide, thereby changing the change in the spin wave propagation characteristics in this region. It can be seen from figure 11 that the complexity of the spin wave intensity mode increases dramatically when the spin wave encounters the defect. The complex diffraction pattern after the defect can be considered as the interference of several modes in the waveguide. As shown in figure 11(b), the spin wave is converted from the fundamental mode to the higher-order mode after passing through the defect due to the spin wave interference caused by the defect. The work of Daniel et al showed that the defect can cause local changes in the internal magnetic field of the waveguide, thereby changing the propagation characteristics of the spin wave. It can be seen from figure 11(b) that defects can not only change the mode of the spin wave but also change the propagation direction of the spin wave. In theory, reasonable use of defects in the design of spin wave devices can build spin wave logic devices with any logic function. Recently, Qi Wang realized the method of inversely designing spin wave devices by using defects, that is, first specifying the function of the spin wave device, and then determining the position and the number of defects through an algorithm, as shown in figure 12. Therefore, it may be feasible to design spin wave devices by making use of the size, number and position of defects to make the spin wave propagation characteristics change locally.

This section introduces two methods of modulating spin waves with microstructure. Both methods directly change the structural parameters of the waveguide. The channelization of spin waves can be controlled by changing the width of the waveguide. The defects in the waveguide can be used to realize arbitrary logic spin wave logic devices. This type of method is suitable for the design of fixed function devices. In addition, this type of method can be combined with the modulation methods described in the following sections to design reconfigurable spin wave logic devices. However, such methods have strict requirements for the process level.

3.1.2. Micromagnetic structure modulation methods. There are a variety of micromagnetic structures (topological magnetic structures) in magnetic media, including vortex, magnetic domain, skyrman, etc. There are special magnetic moment arrangements and internal field distributions around or inside these micromagnetic structures, so the micromagnetic structures also affect the spin wave propagation characteristics around and inside them. The main advantage of utilizing micromagnetic structures to modulate spin waves is that the generation and annihilation of micromagnetic structures can be controlled by external methods (applied magnetic fields, spin-transfer torque effect (STT), spin–orbit torque effect (SOT), etc.), so as to achieve the purpose of dynamic control. In recent years, with the deepening of research on micromagnetic structures, dynamic control of micromagnetic structures such as vortex and skyrman can be achieved in the laboratory, and research on spin wave logic devices related to micromagnetic structures has gradually become favored by researchers.

In magnetic materials with perpendicular magnetic anisotropy, domain walls (DW) interact with spin waves. DW affect the amplitude and phase of spin waves, and spin waves move DW through the spin torque effect. Wojewoda et al studied the propagation characteristics of spin waves with different frequencies after passing through a Néel DW [41]. This experiment utilizes the structure shown in figure 13 to study the propagation characteristics of DESW through DW. Using intensity and phase resolved µBLS experiments, they found that the spin wave with excitation frequency of 7.15 GHz separates into two beams after passing through DW (which is similar to the channelization phenomenon mentioned above), and the spin wave with excitation frequency of 9.00 GHz is confined to the center of the waveguide after passing through DW, as shown in figure 14. In addition, through wavelength fitting and comparison with the single-domain state, the spin wave with excitation frequency of 7.15 GHz has a phase shift of about $0.6\pi$ through DW, and the phase shift of the 9.00 GHz wave is about $0.5\pi$, as shown in figures 14(e) and (f). This experiment revealed the influence of DW on internal magnetic field. This local inhomogeneity leads to a change in the spin wave propagation characteristics in this region.
the propagation characteristics of spin waves. DW affects the phase and propagation characteristics of spin waves. Therefore, the utilization of external fields to realize the generation and annihilation of DW can realize controllable spin wave phase shifts and further realize spin wave logic devices. Utilizing DW can also make structures such as spin wave majority gates simpler. However, DW are highly sensitive to temperature, making it difficult to control the phase shift accurately. Therefore, the implementation of spin wave logic devices based on DW still needs to overcome major difficulties.

Vortex is also a typical topological magnetic structure. In the non-core region of a vortex, the magnetization revolves around the center, while in the core region, the magnetization direction is out of plane. The overall magnetization follows the chirality principle. Park et al studied the propagation characteristics of spin waves after passing through a vortex [42]. In this simulation, the vortex structure is realized by using the two-domain state waveguide, as shown in figure 15. Figure 16 shows the propagation diagram of spin waves through vortex with low (0.18—3.1 GHz) and high (6.4—11.6 GHz) frequencies, respectively. It can be seen from figure 16(a) that the spin wave is well localized in the DW. The spin wave with excitation frequency of 1.8 GHz interacts strongly with the vortex. As the frequency increases, the spin waves scattered to other orthogonal arms gradually decrease. Figure 16(b) describes the spin wave propagation diagram of the other three orthogonal arms at different frequencies. It can be seen that the amplitude and phase of the spin wave change obviously after passing through the vortex, which is related to the frequency. This work introduces a new method of spin wave phase shift. Utilizing this method and setting an appropriate structure one can realize a spin wave majority gate. However, the amplitude of the spin wave is significantly attenuated after passing through the vortex, which is not conducive to the detection of the spin wave and the setting of the threshold of the spin wave logic device.
This section introduces two methods of modulating spin waves using topological magnetic structures. This type of modulation method has strong flexibility. The topological magnetic structures have an influence on the mode, phase and amplitude of spin waves. At present, it is not difficult to realize the generation and annihilation of topological magnetic structures by external means. Therefore, it is feasible to control the topological magnetic structures in combination with an external method to realize a reconfigurable spin wave logic device. However, spin waves have a large attenuation through these topological magnetic structures. How to reduce the loss of spin waves is the biggest challenge in the application of this kind of method. In addition, the generation and annihilation times of topological magnetic structures and the additional spin waves generated in this process also need to be considered.
3.2. Modulation methods of external stimulus source

The magnetic properties of waveguides are affected by many kinds of stimulus sources, such as STT/SOT, dipolar coupling, magnetic fields, electric fields and stress fields. Applying an external stimulus source to waveguides is a direct and efficient way to change the effective field in uniform waveguides. This section introduces several ways of using an external stimulus source to modulate the propagation characteristics of spin waves.

3.2.1. Modulation method of utilizing STT or SOT effects.
Spin-polarized current can interact with magnetic moments and transfer its spin angular momentum to the magnetic moment to realize the reversal of the magnetic moment. This phenomenon is called STT. Another effect similar to its effect is called SOT. The difference between STT and SOT lies in the way the spin current is generated. The influence of STT and SOT on the magnetization dynamics can be explained by the following equation [43]:

\[
\frac{\partial m}{\partial t} = -\gamma m \times H_{\text{eff}} + \alpha m \times \frac{\partial m}{\partial t} + \frac{\gamma}{M_s} \times \tau 
\]  

(17)

where \( M_s \) is the saturation magnetization, \( m = M/M_s \) is the magnetization unit vector, \( \alpha \) is the gyromagnetic ratio, \( H_{\text{eff}} \) is the effective field, and \( \tau \) is the torque term due to STT or SOT.
It can be seen from equation (17) that STT or SOT exerts an additional torque on the LLG equation. In recent years, STT and SOT have been used in magnetic memory due to their fast reversal of magnetic moment characteristics. STT and SOT effects also affect the propagation characteristics of spin waves. STT and SOT are used more to dynamically change the propagation characteristics of spin waves, that is, to design reconfigurable spin wave logic devices.

Figure 16. (a) Diagrams of spin wave propagation with different excitation frequencies. (b) Spin wave propagation diagram of the other three orthogonal arms at different frequencies. Reprinted from [42], with the permission of AIP Publishing.
Most modulation methods utilizing STT adopt the sandwich structure. The sandwich structure is usually composed of a pinning layer, space layer and waveguide. Wang et al proposed a method of controlling the spin wave spectra dynamically in a waveguide based on STT [44]. The simulation structure is shown in figure 17. The comparison between figures 18(b) and (c) shows that STT produces a periodic magnetic structure. This periodic magnetic structure can hinder the transmission of spin waves in a certain frequency band, that is, a forbidden band. Therefore, the generation and annihilation of this magnetic structure can be controlled by STT to control the spin wave transmission in a specific frequency band, as shown
in figure 19. The greatest advantage of this modulation method is that the STT effect can be used for dynamic modulation, which is conducive to the frequency bandwidth expansion and reconfigurability of the spin wave device based on this design. However, the power consumption of the STT effect and the influence of heat on the saturation magnetization of materials are still great challenges for the application of this modulation method. In addition, in recent years, researchers have found that sound waves can be used to assist STT modulation, so as to reduce the power consumption of STT modulation [45].

As a novel effect, the SOT effect has received great attention from researchers in recent years. Compared with the STT effect, the SOT effect has lower power consumption. In addition, the STT effect is an interfacial effect, which is more conducive to miniaturization of the device design. Evelt et al proposed an efficient modulation method to control spin wave propagation in ultra-thin YIG based on SOT [46]. The experimental structure diagram is shown in figure 20. The current flowing into Pt is converted into pure spin current and injected into a YIG waveguide due to the spin Hall effect. The injection of pure spin current results in the SOT effect. The experimental results show that the effective damping of the waveguide has a linear relationship with the current applied by the SOT modulation, as shown in figure 21. The amplitude of spin waves can be amplified in a certain current range. For a long time, how to propagate spin waves over long distances has also been a difficulty in the study of spin wave devices. Although there have been ideas such as spin wave repeaters before this, these methods have not been able to efficiently realize the long-distance transmission of spin waves. It may be possible to realize a spin wave amplifier by applying the SOT modulation method. However, the amplification of spin waves is hindered by Joule heating and the excitation of large-amplitude auto-oscillations. Thus, how to overcome these two problems is key to the application of this modulation method in practice.

This section describes how STT and SOT modulations can effectively hinder or amplify the transmission of spin waves. The advantage of STT and SOT modulations lies in their fast response speed. Although both STT and SOT modulations have the problem of Joule heating, the Joule heating can be reduced by reducing the width of the waveguide or integrating it into the heat-sink devices. In addition, the STT and SOT effects can effectively change the magnetization direction of nanomagnets. To date, there have been studies on the combination of this effect with dipole interaction and spin wave coupling to realize spin wave devices.

3.2.2. Modulation method of applying voltage or strain field. The effect of the aforementioned STT and SOT modulation methods is to apply additional torque to the
magnetization dynamics. Utilizing voltage or stress field modulation is achieved by inducing anisotropic changes in magnetic materials.

The voltage modulates the propagation characteristics of spin waves by voltage-controlled magnetic anisotropy (VCMA). It is more efficient at changing the magnetization dynamics than spin-polarized current because it avoids the generation of Joule heat. Therefore, the voltage modulation method is expected to become a fast and energy-saving magnetization dynamics modulation method in the future. Rana et al proposed reconfigurable nanochannels controlled by VCMA in nano-waveguides [47]. The VCMA effect can locally change the magnetic anisotropy of the waveguide, thereby changing the dispersion relationship of the spin wave locally. As shown in figure 22(b), a positive voltage causes a spin wave dispersion curve of the waveguide with dimensions of 2 µm (length) × 200 nm (width) × 1.3 nm (thickness) to shift downward. Therefore, spin waves with frequencies below the cutoff frequency can propagate locally by changing the magnetic anisotropy. As shown in figure 22(c), the magnetic anisotropy of the waveguide under the Au electrode changes locally, and the spin wave below the cutoff frequency is propagated locally in the nanochannel. The VCMA effect can shift the dispersion curve. Therefore, the VCMA effect can not only localize the spin waves of certain frequency bands in the nanochannel but also locally change the phase of the spin waves, as shown in figure 22(d). This modulation method provides a new idea for modulating spin waves. Compared with STT and SOT, using the VCMA effect to modulate spin waves is more efficient. However, this modulation method requires the thickness of the waveguide to be ultrathin (less than 10 nm). As far as current technology is concerned, it is difficult to achieve a uniform waveguide with such a low thickness.

Strain field modulation is mainly realized by the magnetostrictive effect and its inverse effect. The modulation structure is usually a multiferroic material composed of piezoelectric (PZT) material and magnetostrictive film. Balinskiy et al proposed a spin wave modulator based on a strain field [48], as shown in figure 23(b). The structure consists of a semiconductor substrate, ferromagnetic layer, magnetostrictive layer and PZT layer, as shown in figure 23(a). Spin waves propagate in the ferromagnetic layer. The strain is generated by applying an electric field to the PZT material. The strain acts on the magnetostrictive layer and changes the direction of the easy axis in the magnetostrictive layer. The magnetization of the magnetic strain layer affects the magnetization of the ferromagnetic layer through exchange and dipole–dipole interaction. Finally, due to the change in the magnetization of the ferromagnetic layer, the propagation of spin waves in the ferromagnetic layer changes. The induced voltage is proportional to the amplitude of the spin wave. The magnitude of the stress is proportional to the applied voltage. As shown in figure 23(c), the amplitude of the spin wave and the amplitude of the stress are in a quadratic function relationship. The depth of spin wave modulation is affected by the magnitude of the magnetoelastic field, that is, the magnitude of the voltage. The magnetoelastic field \( H_\text{E} \) is as follows:

\[
H_\text{E} = - \frac{1}{\mu_0 M_s} \begin{pmatrix}
2B_1 \varepsilon_{xx} m_x + B_2 \left( \varepsilon_{xx} m_x + \varepsilon_{xx} m_z \right) \\
2B_1 \varepsilon_{yy} m_y + B_2 \left( \varepsilon_{yy} m_y + \varepsilon_{yy} m_z \right) \\
2B_1 \varepsilon_{zz} m_z + B_2 \left( \varepsilon_{zz} m_z + \varepsilon_{zz} m_y \right)
\end{pmatrix},
\]  

(18)
Figure 21. (a) Spin wave intensity map with $I = 2.55$ mA. (b) Spin wave intensity graph with different currents. (c) Relationship between the decay constant of the spin wave and the current. Reprinted from [46], with the permission of AIP Publishing.
where $B_1$ and $B_2$ are the magnetoelastic coupling constants, $\varepsilon$ is the strain tensor and $m$ is the unit magnetization vector. Although the strain field can change the propagation characteristics of spin waves, this method involves conversion of multiple energies, and the issue of energy conversion rate needs to be considered. Despite the energy consumption problem, the discovery of giant magnetostrictive materials such as Terfenol-D makes the application of this modulation method possible.

This section introduces the propagation characteristics of spin waves modulated by VCMA and a strain field. Compared with STT and SOT modulations, these two modulations do not generate Joule heat. However, these two modulations have higher requirements for material parameters. The development of suitable materials is key to the realization of this type of modulation.

3.3. Modulation method of dipole field

Utilizing a dipole field to modulate the propagation characteristics of spin waves is usually achieved by the dipole interaction between a high-saturation magnetization material and the waveguide. The magnetic dipole energy $E_d$ between two identical magnets can be expressed as [49]:

$$E_d = \frac{\mu_0 M_s^2 V^2}{4\pi R^3} \left( \cos \varphi_2 \sin \theta_2 \cos \varphi_1 \sin \theta_1 - 2 \cos \theta_2 \cos \theta_1 \right)$$

where $\mu_0$ is the permeability of a vacuum, $R$ is the distance between two magnetic magnets, $V$ is the volume of the magnet, $\theta_1$ and $\theta_2$ are the out-of-plane angles of the two magnets, respectively, and $\varphi_1$ and $\varphi_2$ are the in-plane angles. Therefore, it can be seen from equation (19) that the dipole field can be controlled by changing parameters such as the distance between the material and the waveguide and the magnetization direction. The final result of the change in the dipole field is the change in the effective field, so that the propagation characteristics of the spin wave change.

Au et al proposed a spin wave phase-shifting method by placing the resonator vertically [50], as shown in figure 24(a). The resonators (nanomagnets) placed around the waveguide resonate when spin waves propagate in the waveguide. This resonance can produce a constructive or destructive reaction to the spin waves in the waveguide. In particular, the intensity
of this reaction is related to the magnetization direction of the resonators. As shown in figure 24, the spin wave phase shifts in the waveguide when the magnetization direction of the resonator is in-plane, and the resonator absorbs the energy of the spin wave with out-of-plane magnetization, which hinders the transmission of the spin wave. This work provides a new idea for the design of spin wave logic devices. This method modulates the characteristics of a spin wave without direct manipulation of the waveguide, thus avoiding destructive changes to the parameters of the waveguide, such as an increase in damping. If the magnetization state of the resonator can be tuned efficiently and at a high speed, it may be possible to realize a high-speed spin wave logic device or a switching device.

Similar to the previous modulation method, Zhang et al proposed modulating the characteristics of a spin wave using a dipole field generated by a material with high-saturation magnetization [51], as shown in figure 25. In this experiment, the dipole field between Py and YIG affects the effective field on the side of YIG closer to Py. The increase in the effective field on this side increases the wavelength of the edge spin wave propagating on this side, while the spin wave on the other side is hardly affected, as shown in figure 25(b). The transverse placement of high-saturation magnetization materials makes the phase difference and wavelength difference of spin waves which originally propagate in the same phase and at the same wavelength on both sides, as shown in figure 25(c). In general, the dipole interaction between two nanomagnets is related to the distance between the two nanomagnets, the angle between the magnetization directions, the saturation magnetization and other factors. It is very difficult to change the structure parameters such as spacing in the working process of the device. Therefore, if the magnetization direction angle or saturation strength between two nanomagnets can be changed efficiently, the corresponding spin wave logic device function can be realized.

Based on the research of Zhang et al, Lei Zheng et al proposed a design of a broadband XOR logic gate, as shown in figure 26(a) [52]. The structure is composed of an input waveguide, output waveguide and interference Y-type waveguide. Due to the effect of dipole coupling, the wavelength of the spin wave on the side close to Co increases locally. Therefore, π phase shift can be achieved by setting appropriate structural parameters. Based on this feature, this structure can realize the function of a spin-wave XOR logic gate. The local inhomogeneity of the effective field on one side of the YIG waveguide is the main reason for the phase shift. The stray field of the Co element causes this local inhomogeneity. Normally, a fixed structure corresponds to a specific operating frequency. The magnitude of the dipole field is related to the magnetization angle between the materials. The magnitude of the dipole field is directly related to the operating frequency of the XOR gate. Therefore, Zheng et al used the SOT effect to adjust the magnetization direction of Co, thereby adjusting the dipole coupling between Co and YIG. Figures 26(c) and (d) show the results of the SOT effect modulation. Figure 26(c) shows that without the SOT effect modulation, the phase difference of the spin wave with excitation frequency of 4.41 GHz on both sides of the waveguide is greater than π, so the spin wave amplitude of the output waveguide is not 0. After the SOT effect modulation, due to the adjustment of the dipole action between the YIG waveguide and Co element, the phase difference of the spin wave with excitation frequency of 4.41 GHz on both sides of the waveguide is greater than π, so the spin wave amplitude of the output waveguide is close to 0. This method uses the edge-mode spin waves in the same waveguide to achieve spin wave interference, and finally realizes the function of an XOR logic gate. This provides a new method for the design of spin wave devices. However, the current required to expand its
Figure 24. (a) Structure of phase shifter based on resonator. (b)–(d) Out-of-plane magnetization ($m_z$) inside the waveguide at the same relative simulation time for vertical spacing between the resonator and the waveguide kept at 5 nm and changed to 20 and 50 nm, respectively. (e), (f) Propagation diagram of the spin wave in the waveguide with the magnetization of the resonator toggled to the negative $y$ direction. Reprinted from [50], with the permission of AIP Publishing.

operating frequency is relatively large due to the presence of an external bias field. The presence of an external bias field will not only increase the size of the device but also make the integration of the device very difficult. In addition, the presence of an external bias field will increase the power consumption of device modulation. For spin wave devices, DESW or surface waves are the typical choices. However, in order to achieve DESW or surface spin waves ($M \perp k$), the waveguide needs to be magnetized along its short (hard) axis. In order to solve this problem, Haldar et al proposed a waveguide structure composed of nanomagnets [53], as shown in figures 27(a) and (b). This special type of waveguide is designed based on dipole-coupled but physically separated rhomboid-shaped nanomagnets (RNMs). Utilizing the dipole coupling between nanomagnets, the nanomagnets form the waveguide. The shape anisotropy of the nanomagnet is used to make its magnetization direction along the short axis of the waveguide. This structure solves the problem of the bias field cleverly. Haldar et al performed spin wave excitation and detection in this structure. Before spin wave excitation, in order to make all nanomagnets have the same magnetization direction (ferromagnetically ordered (FO) state), Haldar et al initialized all nanomagnets along the long axis, and then removed the magnetic field, as shown in figure 27(c). By using $\mu$-BLS technology, an obvious propagating spin wave mode is observed at 4.2 GHz, as shown in figure 27(d). Although this method avoids the problem of constantly applying a bias magnetic field during initial magnetization. This type of waveguide provides a new idea for the integration of spin wave devices. However, the existence of the initializing magnetic field and the propagation efficiency of spin waves between nanomagnets are still problems that need to be solved urgently by such methods.

This section focuses on some methods of modulating spin waves based on dipole coupling. These methods indirectly change the propagation characteristics of the spin wave through the dipole field. This kind of method can be used not only to design fixed function devices but also to realize reconfigurable logic devices by changing the magnetic state of resonators or placing materials with high saturation magnetization. In addition, the dipole coupling effect also plays an important role in self-biased waveguides. However, the problem with this type of method lies in the power consumption of the device and the propagation efficiency of the spin wave.

4. Summary

Spin waves have the potential to play a major role in the future of the microelectronics industry because of their low energy dissipation and high frequency. Research on the propagation characteristics of spin waves in a uniform waveguide has undergone tremendous progress in the past few decades. Based on these research advances, researchers have come up with
Figure 25. (a) Structure diagram of spin wave phase shift based on dipole action. (b) Effective field diagrams of YIG/Py and single YIG structures. (c) Diagram of spin wave propagation in YIG/Py structure. Reprinted (figure) with permission from [51], Copyright (2019) by the American Physical Society.

many efficient spin wave modulation methods, such as magnetic structure modulation and SOT modulation. This review starts with the propagation characteristics of spin waves in a uniform waveguide, and describes the spin wave dispersion relationship and special propagation phenomena. Then, based on these basic theories, classical spin wave modulation methods are introduced from three aspects: structure, external field and dipole field. Different spin wave modulation methods have different characteristics and application scenarios. The combination of multiple modulation methods may be one of the main directions of spin wave modulation research in the future.

Research on the propagation characteristics and modulation methods of spin-waves has brought about development of spin wave devices with initial success. Spin wave devices have obvious advantages over CMOS devices in terms of
Figure 26. (a) Schematic of SOT-based broadband spin wave XOR logic gate. (b) Simulated spatial maps of the logic gate under all logic inputs. (c) Diagram of spin wave propagation with current density of $J = 0 \text{ A m}^{-2}$ at 4.41 GHz excitation frequency. (d) Diagram of spin wave propagation with current density of $J = 6.0 \times 10^{12} \text{ A m}^{-2}$ under 4.41 GHz excitation frequency. Reproduced from [52]. © IOP Publishing Ltd All rights reserved.
Figure 27. (a) Schematic of RNM-based waveguide. (b) Scanning electron microscope (SEM) image of the RNM waveguide. (c) Magnetic force microscope (MFM) image showing all the RNMs pointing in the same direction (FO state). (d) 2D spatial profile of the spin wave intensity for the FO state. Reprinted from [4], with the permission of AIP Publishing.
energy dissipation and logic structure. However, the integration of spin wave devices and the realization of compatibility with CMOS circuits still face great challenges. A phase shifter based on spin waves is the main part of spin wave logic devices. As mentioned in section 3, there are many ways to realize a spin wave phase shifter. Although methods such as STT and SOT have greatly improved the efficiency of spin wave phase shifting, improving the phase-shifting efficiency and reducing the dependence on an external magnetic field are urgent problems to be solved in the future. In addition, the spin wave coupler plays an important role in the connection of spin wave logic devices. As mentioned in section 2, spin waves propagate in different structures of waveguides; there will be different modes and some special transmission phenomena. Although the spin wave coupler has made great progress in recent years, it still faces great challenges in cascade matching, signal transmission loss and applicable frequency bands. For the application of spin wave devices, devices based on CMOSs are relatively mature and have a high market share. Therefore, spin wave devices should be developed toward compatibility with CMOS devices. Fortunately, using SOT or STT to modulate the spin wave makes compatibility between spin wave devices and CMOS devices possible. With the development of spin wave theory and related process technology, we believe that the integration of spin wave circuits will soon be realized.

Data availability statement

The data that support the findings of this study are available from the corresponding author on reasonable request.

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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