Efficiency of Spin-Wave Bus for Information Transmission

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***Abstract*—We compare the transport parameters such as signal attenuation and signal velocity for a spin-wave bus and a conventional electronic transmission line. The spin-wave bus is inferior to the traditional metal interconnects in all figures-of-merit. The realization of integrated spin-wave-based logic circuits will require spin amplifiers to provide gain.**

***Index Terms*—Magnetic circuits, magnetic films, magnetostatic surface waves, transmission lines.**

It HAS recently been proposed to use spin waves as a physical mechanism for information transmission and processing [1]–[3]. A bit of information can be encoded into the *phase* of the spin wave (e.g., two relative phases of "0" and "π" may be used to represent two logic states 1 and 0, respectively). The data processing in the circuit is accomplished by manipulating the relative phases of the propagating spin waves. Magnetic films can be used as a spin conduit media for wave propagation, or otherwise referred to as the spin-wave bus. In this paper, we discuss two important characteristics of the spin-wave bus: 1) signal propagation speed and 2) signal attenuation.

The speed of signal propagation is defined by the spin-wave group velocity, whereas the dissipation power is defined by the spin-wave damping. To explore the efficiency of the spin-wave bus, we estimate the transport characteristics of the ferromagnetic spin waveguide and compare them with those of a conventional electronic transmission line with the same dimensions. In Fig. 1(a), we have schematically shown the general view of a microstrip and the spin-wave bus. The microstrip consists of a conductive substrate (ground plane), a dielectric layer, and a signal conductor on the top. The dielectric layer has thickness t and relative permittivity ε_r, and the signal conductor has thickness d and width w. The spin-wave bus consists of a ferromagnetic wire on top of a nonmagnetic insulating substrate, which has the same dimensions as the signal conductor ($w = 0.2$ mm, $d = 0.1$ mm, and $t = 10$ μm). Signal propagation in both cases can be represented as a superposition of two waves traveling in opposite directions along with the microstrip or the spin-wave bus. The amplitude of the signal can be expressed as follows:

$$A(z,t) = A_1 e^{-\kappa z}\cos(\omega t - \beta z) + A_2 e^{\kappa z}\cos(\omega t + \beta z) \quad (1)$$

where κ represents the attenuation, and β defines the signal velocity $\nu = \omega/\beta$.

For numerical assets on the spin-wave bus, we use the analytical formula for spin-wave dispersion in a finite-size ferromagnetic film [4], which is given by

$$\omega = \left[\omega_H(\omega_H + \omega_M) + \frac{\omega_M^2}{4}\left(1 - \exp^{-2kd}\right)\right]^{1/2} \quad (2)$$

where d is the thickness of the ferromagnetic film, $\omega_H = \gamma H_0$, $\omega_M = \gamma 4\pi M_s, \gamma$ is the gyromagnetic ratio, and H_0 is the external magnetic field at which film magnetization saturates at M_s. We estimate the spin-wave attenuation $\kappa = (\tau\nu)^{-1}$, where $\tau = (2\pi\gamma\alpha M_s)^{-1}$ is the relaxation time and α is the Gilbert damping coefficient. In our numerical simulations, we used an experimentally found Gilbert coefficient of $\alpha = 0.0097$ from [5], and the material characteristics for NiFe, i.e., $\gamma = 19.91 \times 10^6$ rad/s Oe, $4\pi M_s = 10$ kG, and $H_0 = 200$ Oe, are taken from the literature [6], [7]. Signal attenuation in the microstrip transmission line is estimated by the RLC model described in [8], and the following formulas for the transport coefficients were used:

$$\kappa = \frac{R}{2}\sqrt{2C/L}\left[1 + \left(1 + \frac{\omega_c^2}{\omega^2}\right)^{1/2}\right]^{-1/2}$$

$$\beta = \omega\sqrt{LC/2}\left[1 + \left(1 + \frac{\omega_c^2}{\omega^2}\right)^{1/2}\right]^{1/2} \quad (3)$$

where $\omega_c = R/L$, R is the resistance per unit length, L is the inductance per unit length, and C is the capacitance per unit length. To consider the skin effect, we use the closed-form formulas that are found in [9]. The resistance and inductance per unit length in the high-frequency region asymptotically behave as follows [9]:

$$R'(f) \rightarrow R'_\infty(f) = R'_\infty(f_i)\sqrt{f/f_i}$$

$$L'(f) \rightarrow L'_\infty + R'_\infty(f)/\omega \quad (4)$$

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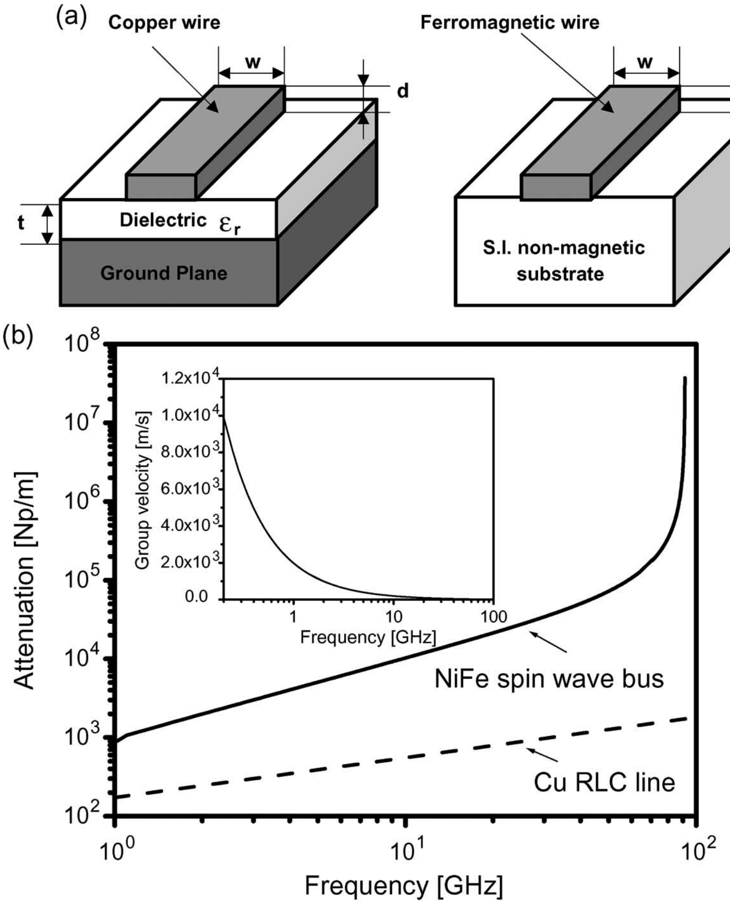

Fig. 1. (a) General view of the microstrip and the spin-wave bus. The microstrip consists of a conductive substrate, a dielectric layer, and a signal conductor. The spin-wave bus consists of a ferromagnetic film on top of a nonmagnetic insulating substrate. The signal conductor and the ferromagnetic film have thickness $d = 0.1\ \mu$m. (b) Results of numerical simulations on signal attenuation in the frequency range from 1 to 100 GHz. Inset: Signal velocity in the spin-wave bus as a function of frequency.

where f_i is a chosen (reference) frequency, R'_∞ denotes the skin-effect resistance per unit length, and L'_∞ is the high-frequency external inductance that is given by $L'_\infty = \varepsilon_0\mu_0/C_0$, where $\varepsilon_0 = 8.8542 \cdot 10^{-12}$ F/m is the permittivity of vacuum, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the vacuum permeability, and C_0 is the transmission line capacitance per unit length in vacuum. The reference skin-effect resistance and inductance were taken for copper ($\sigma = 56$ MS/m) at a reference frequency of 1 GHz: $R'_\infty = 40.64\ \Omega/\text{m}$ and $L'_\infty = 287.6$ nH/m.

In Fig. 1(b), we plot the results of numerical simulations for signal attenuation in the microstrip line and the spin-wave bus in the frequency range from 1 to 100 GHz. The signal attenuation in the microstrip is on the order of 10^3 Np/m. The losses increase with a frequency increase similar to scaling down the thickness of the signal conductor. For the spin-wave bus, our estimates show that the attenuation is on the order of 10^3 Np/m for the gigahertz region, with a rapid increase up to 10^7 Np/m in the high-frequency region of 100 GHz. As can be seen in Fig. 1(b), the signal attenuation in the spin-wave bus is about 1000 times higher than that in the conventional electronic transmission line of the same dimensions even at high frequencies, where the skin effect is prominent. There are different trends for signal propagation speed in the microstrip and the spin-wave bus. At a high frequency ($\omega \gg \omega_c$), the signal velocity in the microstrip approaches its limit, i.e., the speed of light in a given dielectric material. In contrast, the group velocity of the spin-wave signal decreases as the frequency increases. In the inset in Fig. 1(b), we depict the phase velocity of the spin wave as a function of wave frequency. The velocity is on the order of 10^4 m/s at the gigahertz region and decreases as the frequency increases. The results that are shown in Fig. 1(b) are obtained for a specific ferromagnetic material and a specific spin-wave propagation mode $k \perp H$ (magnetostatic surface spin wave). The group velocity varies for different ferromagnetic materials and may be increased by applying an external magnetic field and/or modifying the size of the ferromagnetic wire. However, the fundamental limitation of the spin-wave velocity is due to the finite strength of the exchange interaction between neighboring spins in the magnetic material. For the experimentally studied ferromagnetic materials having a high Curie temperature (for example, cobalt and iron having 1388 and 1043 K Curie temperatures, respectively), the spin-wave group velocity does not exceed 10^5 m/s. Thus, this velocity can be taken as a benchmark for the maximum signal velocity in the spin-wave bus.

Another significant drawback that is inherent to the spin-wave bus is the high signal attenuation. The fundamental cause of spin-wave amplitude damping is the scattering on magnons and phonons, as well as the microeffect of eddy currents in the conducting magnetic materials. Due to the dissipation even in the high-quality low-loss yttrium iron garnet (YIG) films, the propagation length has been found not to exceed 1 cm at room temperature. We would like to outline that the utilization of spin wave for information transmission may be applicable only for short-range in-chip interconnects, which could possibly be suitable in cellular array-based architectures. To realize an integrated magnetic circuit with spin-wave buses, one will need a spin-wave amplifier to provide gain to compensate for losses in the bus. As an example, amplification can be achieved by perpendicular and parallel microwave pumping (up to 40 dB amplification for the input power levels of about 1 pW has been experimentally demonstrated [10]).

Finally, we would like to summarize our conclusions on the spin-wave bus.

1) Spin-wave bus is inferior to traditional metal interconnects in all figures-of-merit.
2) Spin-wave bus can be used for intrachip communication among the spin-based devices and as an interface between electronic and spintronic circuits.
3) The realization of integrated spin-wave-based logic circuits will require the spin-wave amplifier to provide gain and compensate losses in the spin-wave bus.

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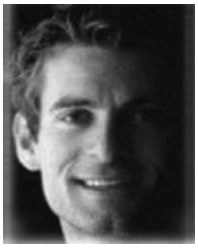

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