A spin wavefront can be created by a few milliwatts of continuous power consumption, while picking up and amplifying the spin wavefront (i.e. the result of the computation) requires several milliwatts to several ten milliwatts of power per output point, depending on the amplifier construction and bandwidth. The data throughput of the device can be several gigabits per second. Based on these estimate, spin-wave-based devices does not seem to be an energyefficient substitute for logic gates, but they may be very efficient as high-frequency, analog signal processors, for example at RF front-ends.

[1] Kozhevnikov, Alexander, Frederick Gertz, G. Dudko, Y. Filimonov, and A. Khitun."Pattern recognition with magnonic holographic memory device." Applied Physics Letters 106, no. 14 (2015): 142409. also Chumak, A. V., V. I. Vasyuchka, A. A. Serga, and B. Hillebrands. "Magnon spintronics." Nature Physics 11, no. 6 (2015): 453-461.

[2] Csaba, G., A. Papp, and W. Porod. "Spin-wave based realization of optical computing primitives." Journal of Applied Physics 115, no. 17 (2014): 17C741.

[3] Breitkreutz, Stephan, Adam Papp, Eugen Egel, Christian Meier, Cenk Yilmaz, Leonhard Heiss, Wolfgang Porod, and Gyorgy Csaba. "Design of on-chip readout circuitry for spin-wave devices." IEEE Magnetics Letters (2016).

[4] Chumak, A. V., A. A. Serga, M. B. Jungfleisch, R. Neb, D. A. Bozhko, V. S. Tiberkevich, and B. Hillebrands. "Direct detection of magnon spin transport by the inverse spin Hall effect." Applied Physics Letters 100, no. 8 (2012): 082405.

[5] Yu, Haiming, O. d'Allivy Kelly, V. Cros, R. Bernard, P. Bortolotti, A. Anane, F. Brandl, F. Heimbach, and D. Grundler. "Approaching soft X-ray wavelengths in nanomagnet-based microwave technology." Nature communications 7 (2016).

P:08 Quantization and analysis of acoustic modes in a rectangular microsound nanowaveguide fixed on a rigid substrate

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Microsound waveguides have been used as delay lines for more than a decade in microwave circuit. With shrinking device sizes there is a need to realize waveguides operating well into the terahertz regime. This article focuses on a waveguide with an isotropic overlay structure deposited on a substrate which has a larger area and much higher rigidity compared to the overlay. Given the known solutions [1] of the completely bound displacement fields inside the overlay; see fig. 1. For the first time the quantization of the displacement fields is performed with respect to normal-mode phonon displacement using following condition [2].

$$\frac{1}{ab}\left[\int_0^a dx \int_0^b dy \left(u_x u_x^* + u_y u_y^* + u_z u_z^*\right)\right] = \frac{\hbar}{2m\omega} \quad (1)$$

where m= mass of the single atom, ω = angular frequency of wave and u_x , u_y , u_z is given by-

$$\left.\begin{aligned} u_x &= \frac{n\pi}{a} A_3 \{ (C(y)-\gamma(y)) + \frac{\Sigma}{\Gamma}[S(y) + \sigma(y) s \frac{g_1}{g_2}]\} \cos(\frac{n\pi x}{a})\, e^{-j(\beta z-\omega t)} \\ u_y &= A_3\{(\frac{\Sigma}{\Gamma} g_1 (C(y)-\gamma(y)) - [S(y) g_1 + \frac{\sigma(y)}{s} g_2]\} \sin(\frac{n\pi x}{a}) e^{-j(\beta z-\omega t)} \\ u_z &= -j\beta A_3 \left\{ (C(y)-\gamma(y)) + \frac{\Sigma}{\Gamma}\left[S(y) + \sigma(y) s \frac{g_1}{g_2}\right]\right\} \sin(\frac{n\pi x}{a}) e^{-j(\beta z-\omega t)} \end{aligned}\right\} \quad (2)$$

$g_1 = \sqrt{\left(k^2 - \frac{n^2\pi^2}{a^2}\right)}$, $g_2 = \beta^2 + \frac{n^2\pi^2}{a^2}$, $C(y) = \cos(g_1 y)$, $\gamma(y) = \cos(sy)$, $\sigma(y) = \sin(sy)$,

$S(y) = \sin(g_1 y)$, $s = \sqrt{\frac{\omega^2\rho}{\mu} - \beta^2 - \frac{n^2\pi^2}{a^2}}$, $\Sigma = 2C_0 - \gamma_0\left(1 - \frac{s^2}{g_2}\right)$ and $\Gamma = 2S_0 + \frac{\sigma_0(g_2^2 - s^2)}{s g_1}$ where

$C_0 = C(b)$, $\gamma_0 = \gamma(b)$, $\sigma_0 = \sigma(b)$, $S_0 = S(b)$, $k = \sqrt{\frac{\omega^2\rho}{\lambda+2\mu} - \beta^2}$, λ and μ are the Lame's constants for the overlay material, ρ (rho) is the density of the overlay material, β and ω are the phase constant and angular frequency of the guided wave and n is a positive integer used for defining the modes. When the quantization condition is satisfied we obtain the constant A_3 as:

$$A_3 = \sqrt{\frac{\hbar}{2M\omega}} . \sqrt{\frac{1}{B}} \quad (3)$$

where $B = \left[\left(\frac{g_2}{2} + \frac{1}{2}\left(\frac{\Sigma}{\Gamma}\right)^2 g_1^2\right) \{ f_s(g_1, b) - 2(f_s(g_1, -s, b) + f_s(g_1, s, b)) + f_s(s, b)\right\} +$
$\left(g_2\left(\frac{\Sigma}{\Gamma}\right) - g_1^{\,2}\left(\frac{\Sigma}{\Gamma}\right)\right)\left(f_c(g_1, b) + f_c(g_1, -s, b) + f_c(g_1, s, b)\right) +$
$\left(g_1 s\left(\frac{\Sigma}{\Gamma}\right) - \frac{g_1 g_2}{s}\left(\frac{\Sigma}{\Gamma}\right)\right)\left(-f_c(g_1, -s, b) - f_c(g_1, s, b) - f_c(s, b)\right) + \left(\frac{g_2}{2}\left(\frac{\Sigma}{\Gamma}\right)^2 + \frac{1}{2} g_1^2\right)\left(1 - f_s(g_1, b)\right) +$
$\left(\frac{g_2}{2}\left(\frac{\Sigma}{\Gamma}\right)^2 2s\frac{g_1}{g_2} + \frac{1}{2}\frac{2 g_1 g_2}{s}\right)\left(f_s(g_1, -s, b) - f_s(g_1, s, b)\right) + \left(\frac{g_2}{2}\left(\frac{\Sigma}{\Gamma}\right)^2 s^2 \frac{g_1^{\,2}}{g_2^{\,2}} + \frac{1}{2}\frac{g_2^{\,2}}{s^2}\right)\left(1 - f_s(s, b)\right)\Big]$
and $f_s(x, y) = \frac{1}{2} + \frac{\sin(2xy)}{4xy}$; $f_c(x, y) = \frac{1}{4xy} - \frac{\cos(2xy)}{4xy}$; $f_s(x, y, z) = \frac{\sin\{(x+y)z\}}{2(x+y)z}$; $f_c(x, y, z) = \frac{\cos\{(x+y)z\}}{2(x+y)z} - \frac{1}{2(x+y)z}$.

The phase characteristics of the system are calculated using dispersion curves and are obtained from the two characteristics equations obtained by solving the generalized displacement fields imposing boundary conditions are given in [1] as:

$$4\theta^2(1-2\theta^2) - \frac{\theta^2\sigma_0 S_0}{\sqrt{(1-\theta^2)(P-\theta^2)}} . \{8\theta^4 - 4(P+2)\theta^2 + (4P+1)\} + \gamma_0 C_0(8\theta^4 - 4\theta^2 + 1) = 0 \quad (4a)$$

$$s = \omega b\sqrt{\frac{(1-\theta^2)\rho}{\mu}} = \frac{(2q+1)\pi}{2} \quad (4b)$$

where $P = \frac{\mu}{\lambda+2\mu}$, $\theta^2 = \frac{\beta^2}{\omega^2} . \frac{\mu}{\rho} + \frac{n^2\pi^2\mu}{a^2\omega^2\rho}$.

Three prominent modes can be seen named Longitudinal (L) and Dilatational (D) obtained from Eq. 4a and Shear (S) phase characteristics obtained from Eq. 4b. Phase characteristics of the three above mentioned modes are analyzed for different height to thickness ratio of the overlay.

The suitability of the waveguide structure to behave as a resonator has been evaluated by calculating frequency-quality factor (f. Q) product taking into consideration intrinsic dissipation of the overlay. The calculation at room temperature is being done by plugging in the parameter for silicon.

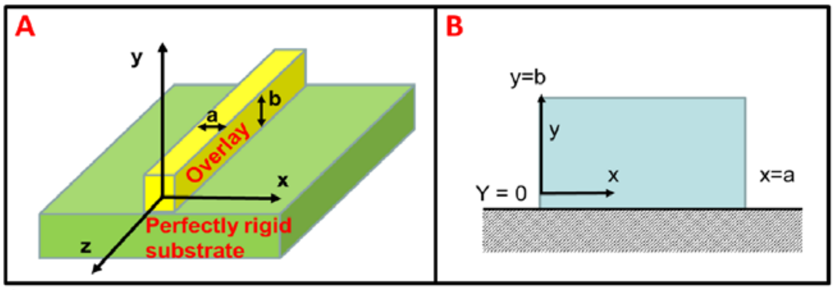

Figure 1: The 3D structure of the microsound waveguide is shown in the fig. A where overlay (yellow) part has much less rigidity compared to the substrate (green) hence substrate assumed to be perfectly rigid. The fig. B shows the rectangular cross-section of the waveguide which is the most common direction for implementing different waveguide structure.

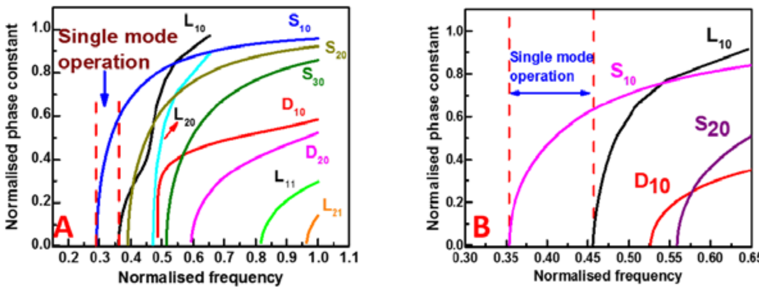

Figure 2: The dispersion curve for the A) b/a =0.3 B) b/a =0.5 ratio is given. The single mode operation window for both the ratio of height/width

[1] Waldron, R.A., 1971. Mode spectrum of a microsound waveguide consisting of an isotropic rectangular overlay on a perfectly rigid substrate. IEEE Transactions on Sonics and Ultrasonics, 18(1), pp.8-15.

[2] Stroscio, M.A. and Dutta, M., 2001. Phonons in Nanostructures. Cambridge University Press.

P:09 Effect of quantum confinement on lifetime of anharmonic decay of optical phonon in a confined GaAs structure

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In this research, the role of phonon confinement on the anharmonic decay of an LO is analyzed. Anharmonic interactions describe the decay of phonon modes in GaAs via the Klemens channel [1]. The interaction Hamiltonian for three phonon process can be written as [2] channel [1]. The interaction Hamiltonian for three phonon process can be written as [2]

$$H_{k,j;k',j';k'',j''} = \frac{1}{\sqrt{N}} P(k,j;k',j';k'',j'')\, u_{k,j} u_{k',j'} u_{k'',j''} \quad (1)$$

where k, k', k'' are the three phonon wave vectors involved in the annihilation or creation process, j, j', j'' are the polarization of the three phonons and N = number of unit cells present. P describes the cubic (anharmonic) coupling. The phonon displacement in normal coordinates is represented as: