Driving coherent phonons and magnons by light

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Phonons and magnons are two fundamental collective excitations in solids, i.e. the quanta of the vibrational motion of the atoms in a crystal lattice and the precessional motion of spins in magnetically-ordered materials, respectively. In the frequency range between 10 and 100 GHz, they have close wavelengths of ~100 nm. When phonons and magnons' wave vectors and frequencies coincide, they form a hybridized state due to magneto-elastic coupling [1]. It gives us additional degrees of freedom in manipulating excitations of both types by light and opens new perspectives for nanoscale communications and data processing [2,3].

The present talk gives an overview of the recent experiments with metallic ferromagnetic nanostructures, in which coherent phonons and magnons of GHz frequencies are excited and detected by ultrashort light pulses [4,5]. While in a metallic ferromagnet, fast dephasing of phonons and magnons typically prevents their strong coupling and long-range propagation, we show how to overcome these limitations. We demonstrate the strong magnon-phonon coupling and the phonon-driven transport of coherent magnons on long distances.

A schematic of the studied structures and the experimental scheme are shown in Figs. 1a and 1b. A layer of Galfenol (a ferromagnetic metallic alloy of Fe and Ga with enhanced magneto-elastic interaction) is deposited on the top of a GaAs/AlAs superlattice grown on the GaAs substrate. Parallel grooves of width w = 30÷100 nm and depth h = 5÷25 nm milled by a focused Ga-ions beam (Raith VELION) form a lateral nanograting with the period d = 100÷200 nm. The optical excitation of the nanograting by the pump pulses (1050 nm, 150 fs, diameter 3 μm, up to 8 mJ cm^{-2}) generates wave packets of the spatially periodic phonon and magnon modes. The excitation is based on instant laser-induced heating, which results in thermal extension of the crystal lattice and modulation of the magnetic anisotropy, respectively [4]. The coherent lattice response is measured by detecting modulation of the reflected linearly polarized probe pulse (780 nm, 150 fs, 0.5 μm diameter, 2 mJ cm^{-2}) due to the photoelastic effect. Rotation of the probe polarization plane due to the magneto-optical Kerr effect serves to detect the spin system's coherent response. The varied time delay between the pump and probe pulses realized in the scheme of asynchronous optical sampling (ASOPS) provides sub-ps time resolution. The transient signals are measured at the spatial overlap of the pump and probe beams and at a distance of up to 100 microns between them.

Figs. 1(c) – 1(e) illustrate the principles of the developed concept. The optically excited wave packet consists of symmetric and antisymmetric surface Rayleigh (R1) and Sezawa (R2) modes and a bunch of the modes localized in the superlattice (W-modes) [5]. The spatial profiles of the selected phonon modes are shown in Fig 1(c). The magnon modes with complex spatial profiles and field-dependent frequencies form the dense discrete magnon spectrum. The external magnetic field, B, applied in the layer plane tunes the magnon frequencies and, thus, their interaction with specific phonon modes. The coupling strength of selected phonon and magnon modes is determined by their spatial overlap. The adjusted magnon-phonon interaction as well as the mode's spectral widths (damping rates), velocities, and spatial localization, determine the spatial-time evolution of the hybridized excitations. An example is the transient Kerr rotation signals measured at several distances from the pump spot, and their fast Fourier transforms shown in Fig. 1(f) and 1(e), respectively. While the surface R-modes demonstrate rapid decay due to scattering at the corrugated surface, the wave packet of W-modes propagates at a distance up to 100 microns. It drives magnons coherently to the distance not available for pure spin waves.

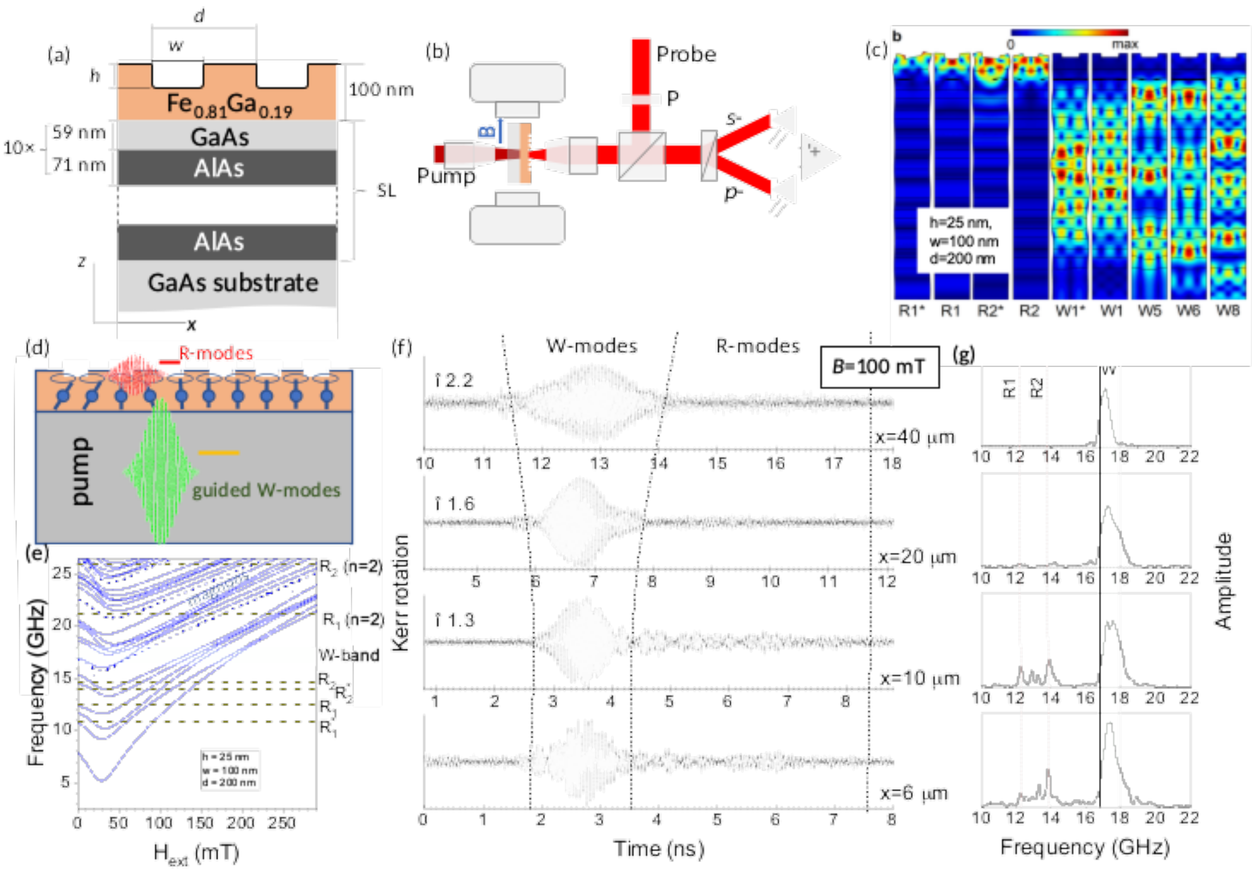

Fig. 1 (a) Schematic of the studied hybrid structures with a ferromagnetic nanograting on the top of a semiconductor superlattice. **(b)** Experimental geometry with the pump and probe beams focused to the spots of 3 and 0.5 mm diameter, respectively, from the opposite sides of the studied structure. The modulation of the probe pulse intensity and polarization is measured in a differential scheme by means of a balanced photoreceiver. **(c)** Spatial distributions of the strain of the several selected phonon modes excited in the studied hybrid structure with h=25 nm, w=100 nm and d=200 nm [5]. **(d)** The experimental idea: a coherent phonon wave packet of the surface (R) and guided (W) phonon modes propagating along the surface drives magnons in the top ferromagnetic layer. **(e)** Calculated magnetic field dependences of the magnon frequencies (blue lines). The red dashed lines and the green dashed rectangular show the field-independent frequencies of the surface phonon modes (R-modes) and the guided modes (W-modes), respectively. **(f and g)** Transient Kerr rotation signals (f) and their fast Fourier transforms (g) measured in the structure with parameters given above at the varied distance x between the pump and probe spots. Time t = 0 ns corresponds to the moment when the pump pulse hits the structure. The spectra shown in (g) are not normalized.

Despite on complexity of the studied system, it is possible to achieve its specific response to the ultrafast optical excitation. We can realize selective coupling of certain magnon and phonon modes with required parameters adjusted by a structural design. Among the range of observed effects, the most interesting ones are the following:

- *Strong coupling of the low order magnon and phonon modes with unprecedently high cooperativity C = 8* [4]. The strong coupling is achieved by the spatial overlap of the selected phonon and magnon modes in combination with their long lifetimes. We show that the symmetries of the localized magnon and phonon states play a crucial role in the magnon-phonon hybridization and its manifestation in the optically excited transient signals.

- *Strongly volatile spatial-time evolution of the guided magnon-phonon wave packet due to the interference of the propagating coupled modes*. The spatial-time volatility results in modification of the transient signal induced by a propagating wave packet detectable with ~100 nm spatial resolution, which is much smaller than the laser spots size.

The talk will present the experimental manifestations of these effects as well as theoretical modelling. We will also discuss potential applications, such as non-conventional computing on the nanoscale.

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