Spin information transfer and transport in hybrid spinmechatronic structures

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Abstract. Spin waves have long been recognized as potential signal carriers in spintronic devices. However, practical development of spin wave based information platforms is its infancy. To date, work in this area has focused on one-dimensional topologies based on purely magnetic thin-film transmission systems, typically exploiting interference phenomena to perform logical operations. In this paper, we describe an alternative approach in which spinmechatronic structures combining spin-wave transmission systems with magnetically loaded micro- and nano-mechanical elements provide spin-information processing functionality.

1. Introduction

Spinmechatronics alludes to the marriage of mechatronics—most particularly micro- and nano-mechanical systems (MEMS and NEMS)—with spin physics and spintronics. Although the term is relatively new, the idea of combining spin and mechanics is certainly not. Many spinmechatronic systems exist, among them a growing range of magnetic MEMS devices (see for example [1–3]) and scientific instruments such as the magnetic resonance force microscope [4–7]. However, as recent advances in fabrication and patterning techniques give life to a rapidly expanding range of micro- and nano-mechanical systems with novel physical properties and functionalities, it is timely to consider how as yet unexplored spin-mechanical synergies may open new routes to expanding our physical insight into magnetic systems of contemporary interest, and/or provide the basis for technologically relevant devices.

In this paper we seek to highlight fresh potential in this hybrid field of research through the description of a particular class of *spin-wave* spinmechatronic system which may find application in information processing.

2. The spin wave as an information carrier

Spin waves are eigenexcitations of the spin-lattice of a magnetic material; the quanta of which are known as magnons. The study of spin-wave systems offers unique fundamental insight into the physics of static and dynamic magnetism as well as a range of general wave and quasi-particle phenomena (see [8–12] and references therein) not readily accessible in other physical domains.

The spin-wave spectrum is traditionally divided into two parts; a region of short-wavelength, low-velocity waves with dynamics dominated by the magnetic exchange interaction, and a longer wavelength region of so-called magnetostatic waves which have higher velocities (typically of order $c/10^4$) and properties governed by the longer-range dipolar interaction [13]. Exchange dominated excitations have a dispersion relationship $\omega(k) \propto k^2$ as derived by the well-known treatment of a one-dimensional Heisenberg chain of spins (see for example [14]). Magnetostatic waves behave very differently and—in typical thin-film experimental systems under conditions of unidirectional magnetic bias—their dispersion depends strongly on the relative orientation of the bias field and their propagation direction [8].

Magnetostatic spin waves (MSWs)—which typically have frequencies in the gigahertz and wavelengths in the micron to millimetre range—are widely acknowledged as a prospective platform for spintronic information transfer and transport (see for example [15–17]); not just by virtue of their ability to function as direct carriers of spin angular momentum but because their unusual dynamic properties potentially conduce to sophisticated information processing capability.

The dispersion properties of linear MSWs can be tuned over a wide frequency and k-vector range using modest externally applied magnetic fields and, owing to their short wavelengths and low velocities in comparison with electromagnetic waves of the same frequency, they are well suited to the demands of micro- and nanoscale device development. Furthermore, in contrast with other physical domains including optics and conventional electronics where the feasibility of nonlinear signal processing techniques is hampered by the intrinsically weak nonlinearity of available materials, nonlinear dynamic phenomena including, for example, soliton and bullet formation, are accessible in certain MSW systems at extremely low power levels (see for example [12, 18, 19]). Artificial magnetic materials, in particular magnonic crystals [20–25]—the spin-wave equivalent of optical photonic crystals—represent a further potential route to information processing functionality, and the appeal of MSW systems is further heightened by their signal storage capability; information may be encoded in the spin-wave mode structure of magnetic elements, and a range of signal storage and restoration mechanisms based on parametric energy transfer between dynamically distinct magnon populations also exist (see [8, 26] and references therein).

3. A spinmechatronic vision for spin wave based information processing

To date, research in the area of magnetostatic spin wave based information platforms has focussed almost exclusively on the development of logical systems based on purely magnetic thin-film transmission systems operating in a linear signal regime. Conceptual gates typically function through the interference of MSWs in Mach-Zehender type structures, driven and detected inductively using microstrip antennas and controlled via current-induced magnetic fields [16, 27]. Whilst the device potential of such systems should not be understated, they are severely limited in the extent to which they capitalize on the rich spin-wave physics outlined above. Moreover, their operational robustness is restricted by the fact that they are low-Q systems in which the efficiency of excitation and detection of waves is intrinsically poor.

Resonant micro- and nano-mechanical elements with Q-factors several orders of magnitude in excess of those accessible in electrical or magnetic systems and operating frequencies in the kHz to MHz range are now readily available. Moreover, the technology to magnetically load or dope them, either via the deposition or application of hard or soft magnetic coatings, particles, or tips [28], is well developed. The exceptional frequency selectivity of these miniature mechanical devices is already exploited in a wide range of scanning probe microscopy techniques and—in an information processing context—strongly recommends them for use both as sensitive narrowband receivers and as a robust, low-power means to write information.

What we propose is a spintronic signalling platform in which information is encoded in the amplitudes and phases of propagating, amplitude modulated magnetostatic spin waves and written and read by resonant magno-mechanical elements. Hybridizing spin-wave physics and miniature mechatronics, such a system potentially combines operational robustness and low power requirements with sophisticated signal processing capability and integrated information storage.

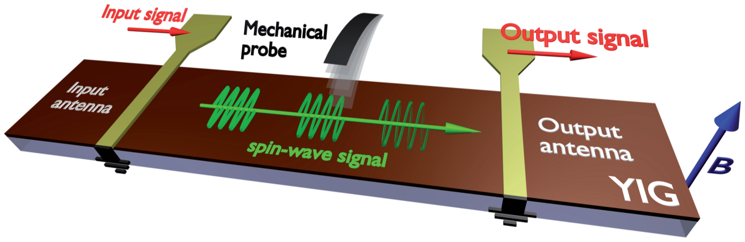

Figure 1. In a recent series of investigations we demonstrated the feasibility of mechanical coupling to propagating magnetostatic waves in a spin-wave transmission structure [29]. In the experiments, amplitude modulated spin waves, excited by a microstrip inductive antenna, were used to drive out-of-plane oscillations of a magnetic micro-mechanical probe (nickel, diameter 10 μm) suspended above the surface of an yttrium iron garnet thin-film spin-wave waveguide. The displacements of the probe were measured using a laser interferometric vibrometer. The same micro-mechanical device was found to be capable of measurably perturbing the amplitude and phase of waves transmitted a distance of 8 mm through the structure. The waveguide was biassed by an out-of-plane field so as to support the propagation of forward volume magnetostatic spin waves.

The success of our spinmechatronic scheme is predicated on the feasibility of two-way interactions between the stray magnetic fields from miniature magno-mechanical systems and *travelling* spin waves. The possibility of mechanical coupling to short wavelength, highly localized spin-wave excitations (generally exchange modes) is well established in the context of magnetic resonance force microscopy [4–7]. However, mechanical coupling to MSWs excited by spatially localized antennas in spin-wave transmission systems—the physics of which is subtly but importantly distinct—has until lately, remained largely unexplored.

Recently, we demonstrated the viability both of detecting amplitude modulated MSWs in a thin-film spin-wave transmission structure via the displacement of a magnetically coupled micro-mechanical probe, and of using the same magnetic probe to modify the phase and amplitude of waves transmitted through it [29]. In our proof-of-concept experiments, we employed an yttrium iron garnet (YIG) waveguide with a nickel probe (diameter 10 μm) suspended above its surface (Fig. 1). The waveguide was biased by a magnetic field applied parallel to the film thickness so as to support the propagation of forward volume magnetostatic spin waves (FVMSW) [13]. In our measurements of spin wave induced oscillations of the mechanical probe, on/off modulated travelling waves were excited in the YIG via an inductive microstrip spin-wave input antenna and displacements of the probe at the modulation frequency detected using a laser interferometric vibrometer (SIOS Meßtechnik GmbH, Nano Vibration Analyzer).

At present, the contemporary capabilities of miniature mechatronics restrict development of the spin-wave spinmechatronic concept to systems with functionality based on resonant interactions between mechanical elements and *amplitude modulated* spin waves driven inductively via microwave currents. However, looking ahead, although not yet widely available, mechanical systems with resonance frequencies well within range of GHz spin waves are now an emerging technology [30]. This invites us to speculate as to whether the spinmechatronic concept we describe could ultimately provide the foundation for a spintronic information platform in which phase-resolved, spin-wave read, write and *drive* operations are undertaken mechanically; entirely without the use of conventional currents.

4. Conclusions

In summary, we have described a proposal for a spinmechatronic signalling platform in which information encoded in the amplitudes and phases of propagating, amplitude modulated magnetostatic spin-waves is written and read by resonant magno-mechanical elements. The system potentially overcomes some of the key limitations of spin-wave information processing topologies proposed to date; affording a robustness and level of functionality surpassing that of purely magnetic, current-controlled schemes.

Proposing the hybrid spin-mechanical structures described in this paper, we seek not only to share a specific device concept, but to stimulate more general discussion around how, by exploring synergies between spintronics and other areas of physics not traditionally associated with the field, we may unearth both new physical insight and as yet unforeseen technological opportunity.

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