Report on benchmarking and technology readiness level assessment of resonant magnonic devices as sources, output couplers, amplitude and phase modulators, and steerers of spin waves

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Abstract

We evaluate resonant magnonic devices, chiral magnonic resonators (CMRs) and magnonic Fabry-Pérot resonators (MFPRs), in terms of their performance as sources, output couplers, amplitude and phase modulators, and steerers of spin waves in the context of magnonic devices developed in project "Magnonic Artificial Neural Networks and Gate Arrays" (MANNGA).

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I. Introduction

Soft magnetic structures located near a magnonic medium can couple to and resonantly scatter spin waves (SWs) travelling in the medium [1,2]. This coupling is mediated by the magneto-dipole interaction between such an overlayer structure and the medium and often has a distinct chiral character. In project "Magnonic Artificial Neural Networks and Gate Arrays" (MANNGA), we use these coupling and resonant scattering to develop a variety of devices, all using continuous thin films of yttrium-iron garnet (YIG) as the magnonic medium. To control SWs propagating in the medium, we explore overlayer structures of two types, leading to two distinctly different resonant scattering effects. The structures of the first type, called here chiral magnonic resonators (CMRs), follow the original ideas from [3-5], whereby the medium and the overlayer are made of the same or similar magnetic materials (Permalloy in [3-5] and YIG in MANNGA), to simplify matching the frequencies of their propagating and local SW modes and to promote their resonant coupling. The structures of the second type exploit Fabry-Pérot resonances [2] formed due to SW reflection from magnonic dispersion mismatches at interfaces between YIG regions with and without a metallic magnetic overlayer; the structures are called here magnonic Fabry-Pérot resonators (MFPRs). In MFPRs, the incident SW energy is resonantly concentrated in the YIG region under the overlayer, rather than in the overlayer itself as in CMRs. So, the frequency of the overlayer's local SW modes may remain much higher than those of the SWs propagating in the medium, and the use of metallic magnetic materials for the overlayers proves fully appropriate.

From their conception, CMRs have been proposed as SW sources [4], modulators [3,5,2], and output couplers [3,4] in emerging magnonic devices. The purpose of this brief report is to summarise results of evaluation of MANNGA's CMRs and MFPRs (as of month 18 of the project) in terms of their performance as (i) sources, (ii) output couplers, (iii) amplitude and phase modulators, and (iv) steerers of SWs, as schematically shown in Fig. 1. The evaluation is performed in the context of CMRs and MFPRs developed elsewhere ('benchmarking') and in the context of the technology developed in MANNGA ('technology readiness level', TRL).

The report is organised as follows. In Section II, we describe the methodology of the assessment. In the subsequent sections, we summarise the evaluation results for SW amplitude and phase modulators (Section III), SW sources (Section IV), SW output couplers (Section V), and SW steerers (Section VI). Section VII contains our conclusions.

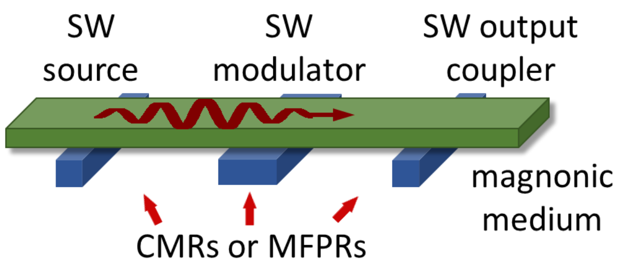

Fig. 1 A generic magnonic device is implemented using CMRs or MFPRs (adapted from [1]). The key constituents of the device are the “SW source”, the “SW modulator”, and the “SW output coupler”. The SW modulator can modulate SW amplitude, phase, and / or direction of propagation. In the latter case, it would perform the function of a “SW steerer”.

II. Methodology

II.A. Technology Readiness Level evaluation

The evaluation of TRLs is done using the following classification from [6]:

- TRL1 - basic principles observed;
- TRL2 - technology concept formulated;
- TRL3 - experimental proof of concept;
- TRL4 - technology validated in lab;
- TRL5 - technology validated in relevant environment;
- TRL6 - technology demonstrated in relevant environment;
- TRL7 - system prototype demonstration in operational environment;
- TRL8 - system complete and qualified;
- TRL9 - actual system proven in operational environment.

For each of the technologies covered by this report, we are working towards TRL3 - experimental proof of concept.

II.B. Benchmarking

Two kinds of benchmarks are considered. The first kind, dubbed ‘MANNGA-specific’ here, deals with demonstrations that could be directly relevant to the devices developed in MANNGA in terms of their basic properties and specifications. The second kind of benchmarks, dubbed ‘ultimate’ here, concern demonstrations that could have vastly different specifications but are based on the same kind of phenomena, i.e. resonant scattering of SWs. In both cases, we identify but avoid quantification of key performance indicators (KPIs) of the devices, for the research in MANNGA is ongoing, while the data available in literature is usually incomplete.

III. Spin wave amplitude and phase modulators

III.A. TRL evaluation for SW amplitude and phase modulation

Figure 2 shows an exemplary data set acquired from a MFPR formed by an 850 nm wide, 10 µm long and 30 nm thick CoFeB stripe patterned (using sputtering, electron beam lithography, and lift-off) on top of an 85 nm thick continuous YIG film. The CoFeB stripe is separated from the YIG film by a spacer layer consisting of 1 nm Tantalum and 3 nm of Tantalum oxide. The device shows a strong modulation of the amplitude and phase of propagating SWs, which can be programmed by switching the orientation of the stripe's magnetisation (Fig. 2) and fine-tuned by varying the strength of the applied bias magnetic field (Fig. 3). This experimental demonstration allows us to assess the TRL of using MFPR for re-programmable and tuneable amplitude and phase modulation of SWs as having achieved TRL3. Figure 2 also shows an excellent agreement between the measurements and numerical micromagnetic modelling, while the latter was also shown to agree with calculations using our phenomenological model (Fig. 3), reported in deliverable D2.3. The calculations can therefore be used to extract any appropriate KPIs and ultimately achieve TRL4.

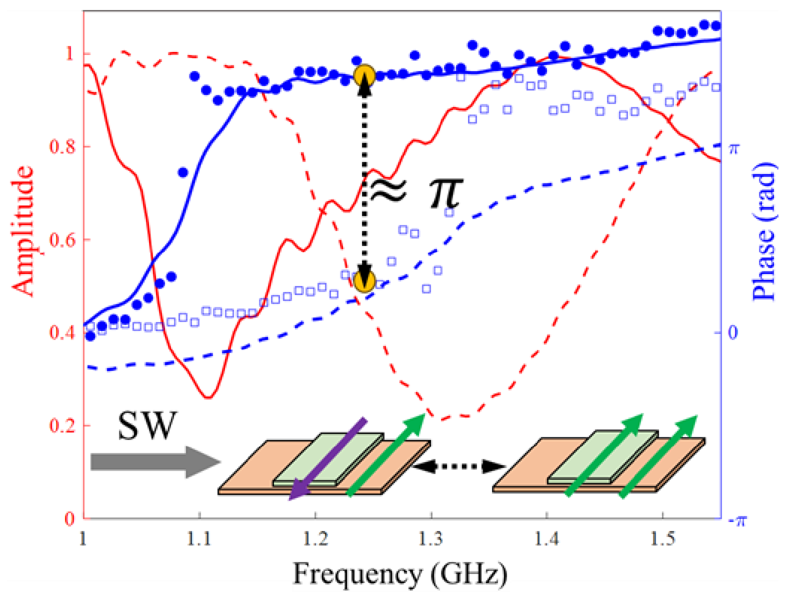

Fig. 2 The amplitude (red) and phase (blue) of the transmission coefficient are shown for an MFPR in different magnetic configurations. The solid / dashed lines and filled / empty symbols correspond to the antiparallel / parallel alignments of the magnetisations in the CoFeB overlayer and YIG medium, as shown in the insets. The lines and symbols are used in plotting simulated and measured results, respectively.

The research for CMR-based SW amplitude and phase modulators has not progressed beyond theoretical calculations (using both micromagnetic and phenomenological modelling) to a successful experimental demonstration. The relevant TRL has not therefore progressed beyond that described in the MANNGA proposal (i.e. TRL2).

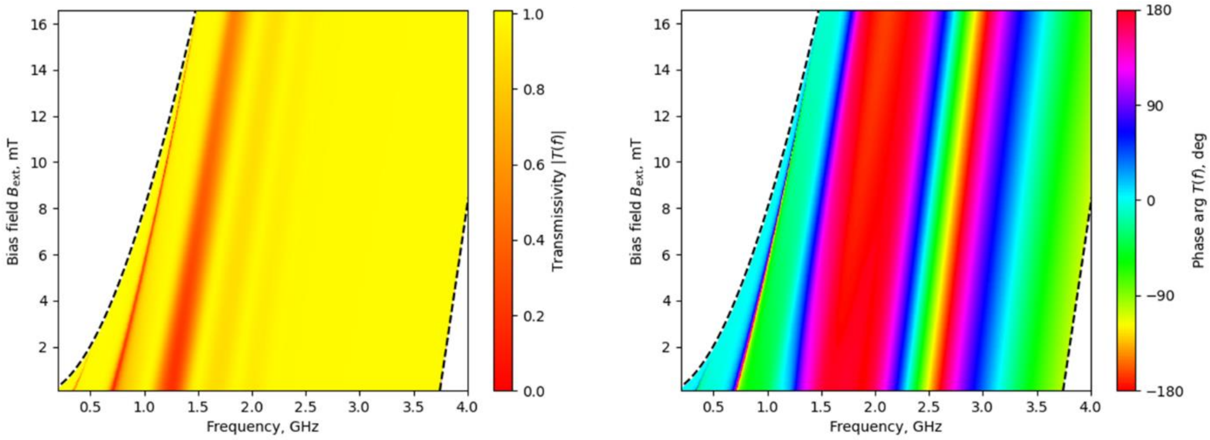

Fig. 3 The amplitude (left panel) and phase (right panel) of the SW transmission coefficient are plotted for an MFPR as a function of the strength of the bias magnetic field.

III.B. MANNGA-specific benchmarks for SW amplitude and phase modulation

Figure 2 suggests that strong *amplitude modulation* can be achieved using the already implemented MFPRs, while any level of amplitude modulation can be achieved, in theory, using CMRs. However, the depth of modulation is not the main KPI from the viewpoint of MANNGA's technological aims. Instead, the width of the transmission is more important: the smaller it is, the stronger energy concentration and so nonlinear effects are expected in the resonator. This points out to using smaller-order (and so, smaller frequency) Fabry-Pérot resonances from Fig. 3 rather than those captured by Fig. 2. The relevant experimental research in MANNGA is ongoing, while the data sets from Fig. 2 and 3 form a natural benchmark and a reasonable target, respectively, for these studies.

Phase-wise, the whole range of phase values is accessible in principle (Fig. 3), and a phase-shift of π is demonstrated experimentally (Fig. 2). Yet, again, the relevant KPIs are more involved than the phase-shift alone. For applications as plain phase-shifters, the phase-shift achieved must be assessed together with the signal energy loss suffered upon transmission. The rate of phase variation with frequency is also important: it must be small for applications as a plain phase-shifter, while it must be large if we are to expect a significant nonlinear effect. Again, the data sets from Fig. 2 and 3 form a natural benchmark and a reasonable target, respectively, for our ongoing research on MFPRs.

The benchmarks set for MFPRs can also be applied to evaluate performance of CMRs (once they are implemented experimentally) for both SW amplitude and phase modulation.

III.C. Ultimate benchmarks for SW amplitude and phase modulation.

Our literature search has not identified any non-MANNGA experimental examples of using either MFPRs or CMRs for amplitude and / or phase modulation of propagating SWs.

IV. Spin wave sources

IV.A. TRL evaluation for SW emission

The use of an all-Permalloy CMR for SW emission was experimentally demonstrated already in [4]. The CMR was dubbed a chiral microwave-to-spin-wave transducer, i.e. a device concentrating the power of incident microwaves [7] and converting it into unidirectional propagating spin waves, while the ability of discrete SW modes of a magnetic nanoelement to launch omnidirectional SWs propagating in a continuous film had been shown already in [8]. This allows us to assess the TRL of using CMRs as SWs sources as having achieved TRL3 already at the start of the MANNGA project. The use of MFPRs as SW sources is conceivable but has not been demonstrated experimentally.

IV.B. MANNGA-specific benchmarks for SW emission

In MANNGA, we have currently opted for using non-magnetic coplanar waveguide (CPW) structures for SW excitation and will adopt existing technology for CMR-based SW sources once this is essential for achieving MANNGA's technological aims. If this happens, the KPIs achievable using non-magnetic CPWs (or microwave transmission lines of other designs) will form a good benchmark for using CMRs as sources of SWs at frequencies / wavelengths required for MANNGA's devices.

IV.C. Ultimate benchmarks for SW emission

The main benefits of using CMRs for SW emission are the magnetically programmable chirality of the emission and its scalability to nanoscale wavelengths, both demonstrated in [4] numerically, but not experimentally. The latter was achieved e.g. in [9], where emission of SWs with sub-50 nm wavelengths and frequencies in excess of 20 GHz was demonstrated, representing a useful benchmark for the technology in general.

V. Spin wave output couplers

V.A. TRL evaluation for SW output couplers

CMR-based SW output couplers exploit resonant absorption or "trapping" of propagating SWs, a phenomenon reciprocal to the SW emission [1]. Shown numerically but not experimentally in [3], its most advanced experimental demonstration to date can be found in [9], again justifying achievement of TRL3 already in 2021. Again, the use of MFPRs as SW output couplers is conceivable based on Fig. 3 but has not been demonstrated experimentally.

V.B. MANNGA-specific benchmarks for SW output couplers

As with SW sources, MANNGA has so far opted for using non-magnetic coplanar waveguide (CPW) structures for SW detection but will adopt existing technology for CMR-based SW output couplers once this is essential for achieving our technological aims. When this happens, the KPIs achievable using non-magnetic CPWs (or microwave transmission lines of other designs) will form a good benchmark for using CMRs as SW output couplers at frequencies / wavelengths required for MANNGA's devices.

V.C. Ultimate benchmarks for SW output couplers

The main benefit of using CMRs as SW output couplers is their scalability to nanoscale wavelengths [4]. The latter was achieved e.g. in [9], where CMR-enabled detection of SWs with sub-50 nm wavelengths and frequencies in excess of 20 GHz was demonstrated, representing a good benchmark for the technology in general.

VI. Spin wave steerers

VI.A. TRL evaluation for SW steerers

Resonant SW steerers exploit resonant absorption of propagating SWs and their re-emission in a new direction. This effect has not been demonstrated and remains at TRL2.

VI.B. MANNGA-specific and ultimate benchmarks for SW steerers

MANNGA-specific and ultimate benchmarks for CMR- and MFPR-based SW steerers coincide, since none has been demonstrated. In such circumstances, the most appropriate benchmarks are given by experiments for non-resonant SW diffraction from [10,11].

VII. Conclusions and outlook

In this report, we have outlined TRLs and benchmarks for such linear magnonic device constituents as sources, output couplers, amplitude and phase modulators, and steerers of SWs. Solid TRL3 has been achieved for SW amplitude and phase modulators, while it is only TRL2 for the other items. The project is currently focusing on development of more complex CMR- and MFPR-based devices, such as chiral magnonic logic gates and gate arrays, enroute to which we should still see achievement of TRL3 for the linear magnonic device constituents.

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