# Reprogrammable hybrid magnonic materials via spin-wave coupling to single-molecule magnets

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Magnon-based electronics offers a promising route toward next-generation logic devices by addressing the scaling and energy-efficiency limitations of conventional CMOS technologies [1]. The long-distance propagation of spin waves (SWs) in low-damping magnetic materials enables information transport without charge motion; however, precise control of SW propagation at the nanoscale remains a central challenge for the realization of compact, highly interconnected magnonic circuits [2]. While a key advantage of SW-based computing lies in the ability to form dense two-dimensional networks through coupling between multiple channels or resonators, achieving strong and controllable interactions between propagating spin waves and localized spin systems remains highly nontrivial.

In this work, we propose and numerically investigate a novel class of reprogrammable hybrid magnetic materials designed to provide strong and tunable spin-wave control at deep nanoscale dimensions. The studied platform consists of a thin yttrium iron garnet (YIG) film decorated with an ordered array of $Mn_{12}$-based single-molecule magnets. Single-molecule magnets (SMMs) are particularly attractive in this context, as they exhibit high-spin ground states, excited electronic spin levels, magnetic bistability at low temperatures, and long quantum coherence times, making them promising candidates for quantum computing and spintronic applications [3]. Importantly, SMMs can be integrated onto nanostructured substrates while preserving their intrinsic magnetic properties, thereby enabling novel hybrid magnonic architectures. Previous experimental studies have demonstrated the technical feasibility of depositing $Mn_{12}$ molecules onto surfaces and controlling their spatial distribution. Chemical immobilization and spontaneous self-assembly enable molecular deposition with inter-molecular separations down to a few nanometers, providing statistical control over surface distributions [4]. Moreover, long-range ordering of molecules can be achieved using stamp-assisted deposition or by employing porous silica templates deposited on YIG to guide the arrangement of SMMs [5].

Within the framework of the study, micromagnetic simulations complemented by finite-element analysis and coupled-mode theory are employed to analyze spin-wave dispersion relations and transmission spectra in the YIG/$Mn_{12}$ hybrid system. We demonstrate that periodically arranged molecular magnets enable resonant coupling between propagating SWs and molecular magnetic moments, resulting in the opening of a well-defined gap in the transmission spectrum. Our results show that the coupling strength, manifested in both the width and frequency position of the anticrossing gap, can be tuned by adjusting the external bias magnetic field or modifying the molecular arrangement. Furthermore, we demonstrate the reprogrammability of the system through the formation of molecular clusters with antiferromagnetically aligned magnetic moments, providing additional control over the spectral characteristics of the SW–molecule interaction. These findings highlight the potential of integrating molecular-scale magnetism with low-damping magnonic substrates to realize scalable, multifunctional, and reconfigurable platforms, paving the way toward advanced magnonic information processing and molecular-based neuromorphic computing architectures.

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