

High Frequency Micro-Patterned Fe₆₅Co₃₅ Thin Film with Tunable FMR and Permeability for RF Passives

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Primary CNF Tools Used: Microwave Small-Signal Probe Station and Electronics, Heidelberg MLA 150 Maskless Aligner, Keyence VHX-7100 Digital Microscope, SC4500 Odd-Hour Evaporator, AJA Sputter 3

Abstract:

This work presents a unique design method and optimization of high frequency magnetic patterns with controllable effective permeability and ferromagnetic resonance behavior for integrated microwave devices. Thin-film micro-patterned FeCo array with initial permeability of 42.7 has been fabricated to achieve a high FMR of 18.1 GHz. Independent control of magnetic properties of the pattern array has been realized by changing pattern spacing, showing a FMR tuning range of 2.20 GHz, with little change in effective permeability. Noise suppression and inductance enhancement at high frequencies (> 10 GHz) have been demonstrated for RF applications by integrating the proposed magnetic pattern array with coplanar waveguides (CPW). Our method shows a high degree of freedom and flexibility for designing high frequency integrated magnetic microwave components.

Summary of Research:

Fast growing demand of higher data rate, low latency, high quality of service in wireless communication systems calls for RF front-end devices that are frequency agile, miniaturized and multifunctional. Novel materials, structures and technologies have been explored to improve performance and bring new functionality for RF devices. Integrating high-performance novel magnetic materials into on-chip RF devices shows promising results in enhancing inductance, miniaturizing devices, suppressing interference and achieving non-reciprocity and tunability. Previous works have demonstrated the application of integrated magnetic materials in inductors, isolators, antennas, filters, and noise suppressors.

However, integrating magnetic materials for high frequency applications is particularly challenging. Limited by the relatively low ferromagnetic resonance

(FMR) frequency, radio-frequency (RF) devices (e.g., on-chip inductors) integrated with common ferromagnetic materials consistently operate only at sub-GHz or up to a few GHz. While the FMR frequency can be increased by applying bias magnetic fields, this approach reduces the permeability of magnetic materials due to an intrinsic FMR-permeability tradeoff, therefore limiting the device performance. In addition, integrating large, localized bias magnetic fields with monolithic microwave circuits is highly impractical. Finally, the high loss of most ferromagnetic materials, especially near FMR frequency presents additional challenges for their device integration. Thus, novel magnetic materials with controllable high frequency characteristics are highly desired in microwave applications.

Previous work has shown promising results of improving FMR to a few GHz by patterning ferromagnetic thin films, yet no control of magnetic properties or design optimization of the magnetic pattern array has been proposed. In this work, we dramatically increase the FMR frequency of ferromagnetic patterns at zero field bias to 18.1 GHz, while maintaining a high broadband permeability of 42.7. An analytical model has been established to independently control and optimize the magnetic properties (ω_{FMR} and μ_r) of the patterned array by changing pattern spacing along two orthogonal axes. The proposed magnetic pattern array was integrated with CPWs to demonstrate its high frequency RF application for noise suppression and inductance enhancement. Our optimization approach allows for the facile design of integrated microwave magnetic components.

Conclusions and Future Steps:

In this work, we demonstrate design, tuning and optimization of patterned ferromagnetic thin film arrays for high frequency MMIC applications. The

FMR frequency of high permeability ferromagnetic patterns was increased to around 18 GHz (Ku band) for the first time. An analytical model was established, and a design method is proposed to independently tune the FMR, effective permeability of the magnet pattern array for optimal integrated device operation. The proposed pattern arrays were integrated with CPWs to experimentally demonstrate their RF applications as noise suppressors and inductors. Our method is highly versatile and provides a high degree of freedom for designing high frequency tunable magnetic properties for integrated microwave systems. In the future, we will implement a magnetic fully integrated inductor that works that high frequencies, and achieve tunability via magnetoelectric coupling.

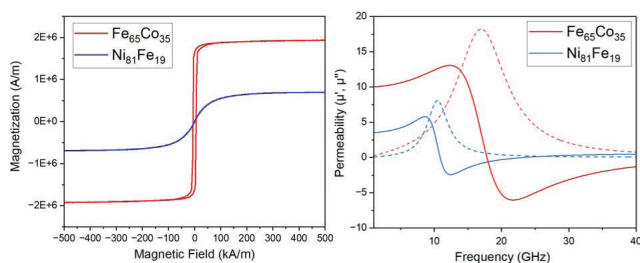


Fig. 1. Magnetic characterization M-H loops (left) of Fe65Co35 compared with Ni81Fe19 and frequency dependent permeability (right) calculated from the Landau-Lifshitz-Gilbert (LLG) model. The solid line and dash line represent the real part and imaginary part, respectively.

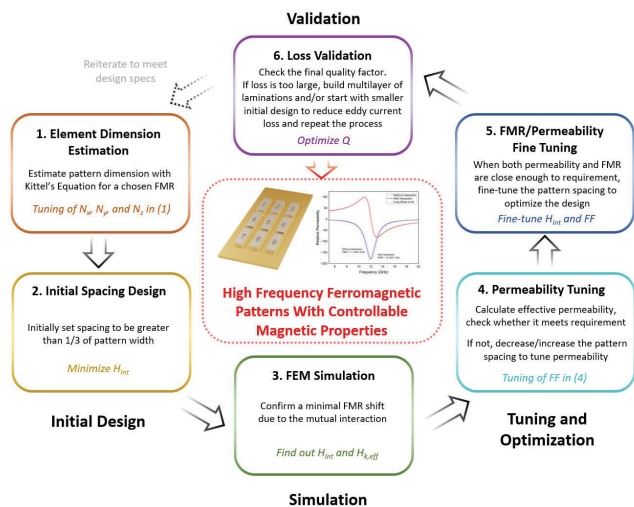


Fig. 2. Design flowchart for high frequency ferromagnetic patterns with controllable magnetic properties.

References:

- [1] A. El-Ghazaly, R. M. White, and S. X. Wang, "Gigahertz-Band Integrated Magnetic Inductors," *IEEE Trans Microw Theory Tech*, vol. 65, no. 12, pp. 4893–4900, 2017, doi: 10.1109/TMTT.2017.2728040.
- [2] M. Yamaguchi et al., "Performance of integrated magnetic thin film noise suppressor applied to CMOS noise test chips," in 2011 41st European Microwave Conference, 2011, pp. 49–52. doi: 10.23919/EuMC.2011.6101991.
- [3] Y. Zhang et al., "Nonreciprocal Isolating Bandpass Filter With Enhanced Isolation Using Metallized Ferrite," *IEEE Trans Microw Theory Tech*, vol. 68, no. 12, pp. 5307–5316, 2020, doi: 10.1109/TMTT.2020.3030784.
- [4] Y. He et al., "Integrated Tunable Bandstop Filter Using Self-Biased FeGaB/Al2O3 Multilayer Thin Film," *IEEE Trans Magn*, vol. 54, no. 9, pp. 1–4, 2018, doi: 10.1109/TMAG.2018.2851579.
- [5] H. Chen et al., "Integrated Tunable Magnetoelectric RF Inductors," *IEEE Trans Microw Theory Tech*, vol. 68, no. 3, pp. 951–963, 2020, doi: 10.1109/TMTT.2019.2957472.
- [6] D. S. Gardner, G. Schrom, F. Paillet, B. Jamieson, T. Karnik, and S. Borkar, "Review of On-Chip Inductor Structures With Magnetic Films," *IEEE Trans Magn*, vol. 45, no. 10, pp. 4760–4766, 2009, doi: 10.1109/TMAG.2009.2030590.
- [7] T. Wang et al., "Integrating Nanopatterned Ferromagnetic and Ferroelectric Thin Films for Electrically Tunable RF Applications," *IEEE Trans Microw Theory Tech*, vol. 65, no. 2, pp. 504–512, 2017, doi: 10.1109/TMTT.2016.2616869.
- [8] J. A. Osborn, "Demagnetizing Factors of the General Ellipsoid," *Physical Review*, vol. 67, no. 11–12, pp. 351–357, Jun. 1945, doi: 10.1103/PhysRev.67.351.
- [9] W. R. Eisenstadt and Y. Eo, "S-parameter-based IC interconnect transmission line characterization," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 15, no. 4, pp. 483–490, 1992, doi: 10.1109/33.159877.

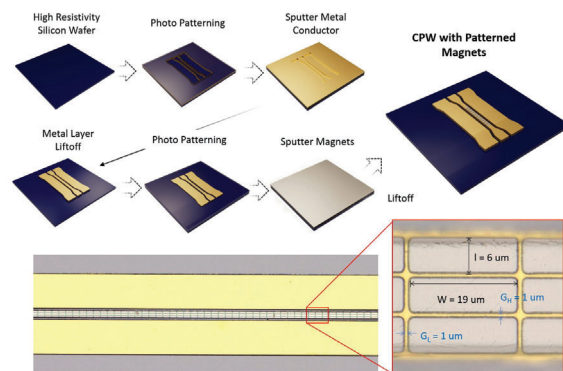


Fig. 3. Fabrication process and microscopic image of the Fe65Co35 magnet patterned CPW.

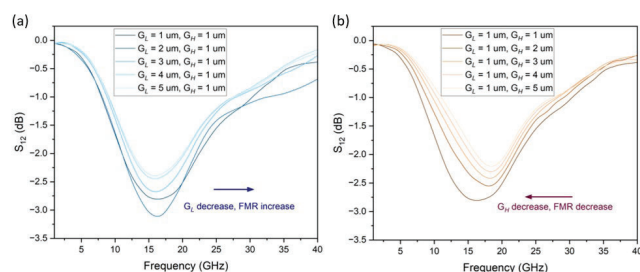


Fig. 4. Measured S12 parameters of noise suppressors when changing gaps of magnets along the (a) longitudinal (b) horizontal direction.