

Integrated metal magnetic film coupled line circulators for monolithic microwave integrated circuits

J.W. Wang, S.D. Yoon, V.G. Harris, C. Vittoria and N.X. Sun

A new structure of integrated planar metal magnetic film coupled line (MMFCL) circulators is presented, in which a metal magnetic film is used instead of ferrite materials. Simulation was performed with HFSS based on coupled-mode theory. An insertion loss of 4 dB and isolation of -13.5 dB between S_{21} and S_{12} over a frequency band of 3 GHz (from 36.5 to 39.5 GHz) were realised for a three-port MMFCL circulator.

Introduction: Ferrite coupled line (FCL) and FCL circulators originated from the early experimental work of Davis and Sillars in 1986 [1]. Through coupled-mode analysis, Mazur and Mrozowski [2] found in 1989 that the even mode and odd mode of a weakly magnetised FCL became coupled when the ferrite was longitudinally magnetised. Teoh and Davis proposed a normal mode theory in 1995 to alleviate the weak coupling assumption in coupled-mode theory [3]. In 2000, Xie and Davis [4] developed a full-wave normal-mode analysis and explained the non-reciprocal effect of the magnetised FCL in terms of the eigen modes and the decomposition coefficients. According to coupled-mode theory, the optimal operation condition for the weakly magnetised FCL is equal propagation constants for the odd mode and for the even mode, i.e. $\beta_{\text{even}} = \beta_{\text{odd}}$ [2]. The length of the ferrite coupled lines (FCL) for a three-port circulator can be determined by $CL = \pi/4$, where L is the length of the FCL, and C is the coupling coefficient proportional to the off-diagonal component of the permeability tensor of the ferrite.

Ferrite coupled line and FCL circulators have been reported with a low insertion loss of 0.5 dB, large isolation of -15 dB, and a wide bandwidth of 50 GHz [5–7]. They have attracted attention recently owing to the many advantages they offer over junction circulators [5–7]. First, FCL circulators utilise ferrites disks with in-plane magnetisation, thus only a weak bias magnetic field is needed. Secondly, FCL circulators have very large bandwidth [5–7].

Metal magnetic films and the associated micro-fabrication technologies provide great opportunities for integrated magnetic microwave devices for MMICs. Several reasons exist. First, metal magnetic films and the associated fabrication technologies are low temperature processes compatible with MMIC technologies, and have been widely used in the information storage industry. Secondly, metal magnetic films have a high saturation magnetisation up to 24.5 kG, narrow ferromagnetic resonance linewidth comparable to those of ferrites, and high squareness (remanence ratio M_r/M_s) of $\sim 100\%$ [e.g. 8], making it possible to achieve self-biased magnetic microwave devices with metal magnetic films. In fact, integrated tunable magnetic micro-strip bandstop filters have already been demonstrated with metal magnetic thin films [8–10].

In this Letter, a new design for integrated metal magnetic film coupled lines (MMFCL) and MMFCL circulators is presented, which use metal magnetic films instead of ferrite materials. HFSS simulations show that these MMFCL and MMFCL circulators have great potential for applications in a wide frequency range.

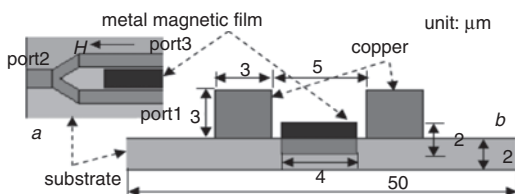


Fig. 1 Structure of MMFCL in-planar circulator and MMFCL

a MMFCL in-planar circulator, top-down view
b MMFCL, cross-section view

MMFCL and MMFCL circulator design: The new design for the metal magnetic film coupled lines (MMFCL) is shown in Figs. 1a and b for the top-down and cross-section views of the MMFCL, respectively. The MMFCL is based upon the microstrip transmission line, of which the metal magnetic film has the shape of a long strip in between

the two Cu lines instead of a whole layer. Compared to a full metal magnetic film, the magnetic strip leads to weakened coupling between the even mode and odd mode, which will in turn increase the circulator's length. However, the insertion loss of the circulator can be significantly decreased, which makes MMFCL possible.

A three-port MMFCL circulator is designed by cascading the MMFCL with a T junction, as shown in Fig. 1a, similar to the three-port FCL circulators [5–7]. For realistic dimensions of the MMFCL circulators at ~ 40 GHz an MMFCL with length of ~ 8 mm, and width and thickness of the magnetic strip of ~ 4 and 2 μm , respectively is required. Owing to the strong shape anisotropy associated with the long 'needle' geometry of the metal magnetic strip in an MMFCL ($8000 \times 4 \times 2$ μm), there is a strong effective uniaxial anisotropy field $H_A \sim 2\pi M_s$ (cgs unit) along the length direction of the MMFCL, which provides the bias magnetic field for the MMFCL circulator. A magnetic field of 5000 Oe is applied along the longitudinal direction as indicated in Fig. 1 for the purpose of achieving an operation frequency ~ 40 GHz

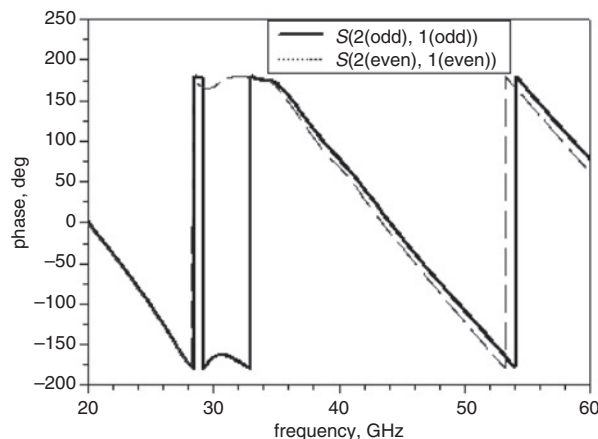


Fig. 2 Phase response curve of MMFCL

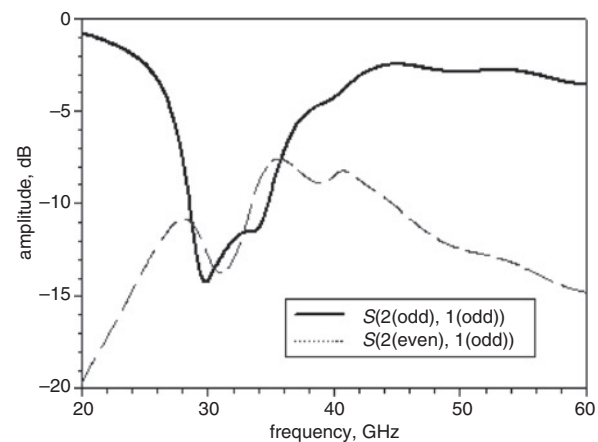


Fig. 3 Amplitude response curve of MMFCL

$S(2(\text{odd}), 1(\text{odd})$ input is odd signal and output odd signal
 $S(2(\text{even}), 1(\text{odd})$ input is odd signal and output odd signal

Predicted performance: The design dimensions for the MMFCL are shown in Fig. 1b for an MMFCL working at ~ 40 GHz. Permalloy ($\text{Ni}_{81}\text{Fe}_{19}$ (wt%)) with a saturation magnetisation of 10 kG and a ferromagnetic resonance linewidth of 200 Oe was used in the simulation. A single layer of magnetic material is used in simulation for computation time-saving purpose. Fig. 2 shows the phase of $S(2(\text{odd}), 1(\text{odd}))$, and $S(2(\text{even}), 1(\text{even}))$. They are a reflection of the phase velocity of the even mode and odd mode. The close phase angle of the $S(2(\text{odd}), 1(\text{odd}))$, and $S(2(\text{even}), 1(\text{even}))$ at ~ 40 GHz indicates that the optimal operation condition of $\beta_{\text{even}} = \beta_{\text{odd}}$ is achieved. Fig. 3 is the amplitude response of $S(2(\text{odd}), 1(\text{odd}))$, and $S(2(\text{even}), 1(\text{odd}))$. Ideally, they should be equal to -3 dB, which means half of the energy of the odd mode is transferred into the even mode. The discrepancy (~ 4.3 dB at 40 GHz) could be because the MMFCL length is not optimised (needing to be longer), and that the MMFCL is lossy. The amplitude response of the circulator is shown in Fig. 4. We

can see that, from 36.5 to 39.5 GHz, S_{21} and S_{32} are larger than -4 dB and S_{12} , S_{23} , S_{31} are lower than -13.5 dB. S_{13} is more lossy, from -5.7 to -4.9 dB in this frequency band, because the signal from port 3 to port 1 has to travel double the length compared to S_{21} and S_{32} . The MMFCL performance is expected to improve when a soft magnetic metal/insulator multilayer is used, which can significantly reduce eddy current loss.

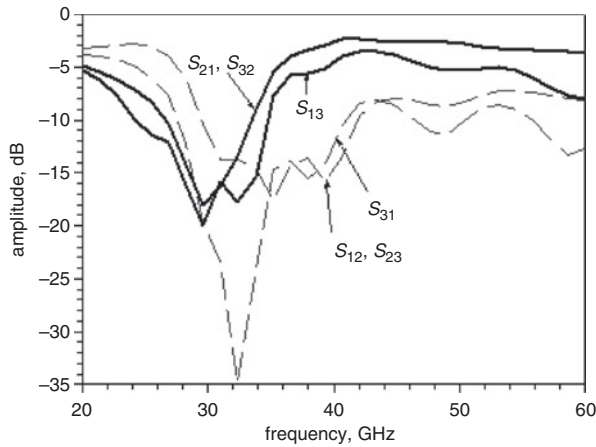


Fig. 4 Predicted performance of three-port MMFCL in-planar circulator

Discussion: The magnetic properties and the dimensions of the metal magnetic strip in the MMFCL will determine the effective permeability tensor of the metal magnetic/dielectric composite substrate beneath the two copper conductors. The off-diagonal permeability component μ_a is proportional to C , the coupling coefficient between the even mode and the odd mode, which will determine the length of the device. By carefully tuning the dimension (particularly the thickness) of the magnetic film, equal propagation constants for the odd and even modes can be achieved. Fortunately, the thickness of the magnetic film for achieving equal propagation constants for the even and odd modes for typical MMFCL structures is between $1\text{--}2\ \mu\text{m}$, which is readily achieved by PVD processes or by electroplating.

The MMFCL circulators have unique advantages. First, the planar processing technologies at room temperatures for MMFCL circulators are fully compatible with MMIC technologies. Secondly, further miniaturisation can be achieved for MMFCL circulators owing to the much higher achieving saturation magnetisation in metal magnetic films compared to ferrites. Lastly, large achievable squareness of metal magnetic films allows for a self-biased MMFCL circulator.

Conclusions: The structure and performance of the magnetic metal film coupled line and MMFCL circulator have been presented.

MMFCL circulators are designed with 4 dB insertion loss (for S_{13} , 5.7 dB), -13.5 dB isolation from 36.5 to 39.5 GHz, and a bandwidth of 3 GHz. It is notable that the MMFCL design is far from being optimised. With improvement of impedance matching and coupling, and with application of soft magnetic metal/insulator multilayers, the length and the loss of the MMFCL and MMFCL circulators are expected to decrease.

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J.W. Wang, S.D. Yoon, V.G. Harris, C. Vittoria and N.X. Sun (*Center for Microwave Magnetic Materials and Integrated Circuits (CM3IC), Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115, USA*)

E-mail: nian@ece.neu.edu

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