Magnetic Nanowires based Reciprocal & Non-reciprocal devices for Monolithic Microwave Integrated Circuits (MMIC)

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ABSTRACT

The use of nanowires as a tunable stop-band notch-filter (reciprocal device) in a coplanar waveguide (CPW) geometry has been assessed. The stop-band frequency (f_r) is observed to be tunable up to 24 GHz with an applied field (H) of 6 kOe in a parallel configuration and up to 14 GHz with an applied field (H) of 4 kOe in perpendicular configuration. Use of nanowires as microwave resonance-isolators (non-reciprocal devices) are realized and measured. The isolator is designed in the principle of a waveguide based E-plane resonance isolator. The attenuation of the wave in forward and reverse direction results a difference in transmission coefficients that shows a non-reciprocal effect. The isolation is ~ 6 dB/cm at 23 GHz. The bandwidth of the device is relatively large (5-7 GHz) in comparison to ferrite-based devices.

Keywords: Nanowires, NA-FMR, band-stops filter, isolator

1 INTRODUCTION

The dynamic properties of magnetic submicron-size wires are of great importance in the magnetization reversal process and to design high frequency active and passive components. Magnetic microwave devices have been made with dielectric and magnetic substrates [1-4]. Ferrites [1-2] and metallic films [3] are used for their magnetic properties that can be controlled by a magnetic field.

Reciprocal devices such as phase shifters and band-stop filters have been constructed out of both ferrites and metallic films. However, nonreciprocal devices, such as isolators, have only been constructed with ferrites. An isolator is a device allows wave propagation in one direction but has significant attenuation for propagation in the reverse direction. Isolators can be used, for example, in preventing frequency instability of the microwave oscillator by reducing the reflected wave from the load.

Isolators operate in a frequency range that depends on the external field, H, and on the saturation magnetization ($4\pi M_S$). Ferrites are typically characterized by a low saturation magnetization and their operating frequencies are generally below 10 GHz. The frequency range can be increased by using ferromagnetic metals [3] because of their high saturation magnetization (for Fe, $4\pi M_S$=21.5 kG). However, the presence of a metal has drawbacks. For example, the occurrence of eddy currents in the metal results in energy losses that significantly damp electromagnetic waves. Furthermore, the same currents tend to screen out electromagnetic waves, which gives a skin depth on the order of 1 μm at 10 GHz. In this investigation we use a hybrid structure that combines the high $4\pi M_S$ of a ferromagnetic metal (nickel) in the form of nanowires with the extremely high dielectric alumina matrix to develop both reciprocal and nonreciprocal tunable microwave devices.

2 EXPERIMENT & FABRICATION

The Ni nanowires were grown into a hole-pattern of commercial anodized alumina templates (Anodisc 25, Whatman) of 60 μm in thickness and 200 nm in nominal pore size. The templates were used as is. Nickel was electrodeposited into porous alumina templates to create ordered nanowires. To accomplish this, the alumina template was first painted with a gallium-indium eutectic (Aldrich) on one side to allow for electrical conduction. The painted side was placed in contact with a copper plate (32 mm x 51 mm). The copper plate was partially covered with electrical tape to prevent any unwanted deposition. The exposed part of the plate was used for making electrical contact. The copper plate along with the attached template was submerged in a nickel plating solution (Watts Nickel Pure, Technic) which completely covers the top of the membrane. For the anode, a nickel wire (99.98% pure, Goodfellow) of 1.0 mm diameter was used. Electrodeposition was carried out using a potentiostat at 1.5V and a constant current of 100 mA. The deposition time was varied to control the lengths of the nanowires.

After electro-deposition, nitric acid was used to dissolve the conductive layer of GaIn paint. The nanowires were also prepared for TEM measurements by soaking the membrane in a 6M NaOH solution for 30 minutes. The separated nanowires were cleaned several time with deionized water and finally suspended in ethylene glycol solution for the TEM measurements. After TEM imaging, the wires were found to have a typical radius of ~150 nm (Fig.1).

The monolithic microwave devices were fabricated on top of the alumina templates filled with Ni nano-wires. A thick layer of Cu (~ 1.2 μm) was deposited by magnetron sputtering. Photolithography and etching

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techniques were used to define a coplanar waveguide (CPW) transmission line structure as shown in Figure 2.

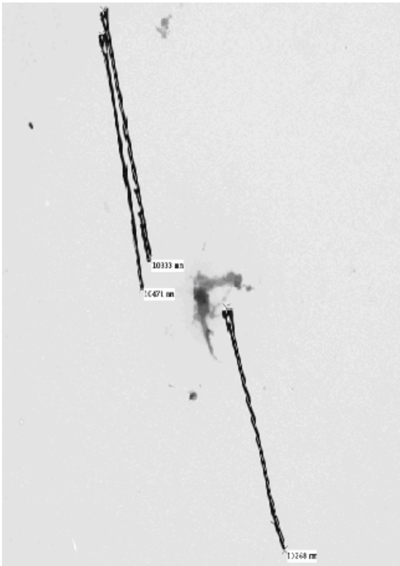

Figure 1: TEM image of nickel nanowire (11 μm length) extracted from the alumina template.

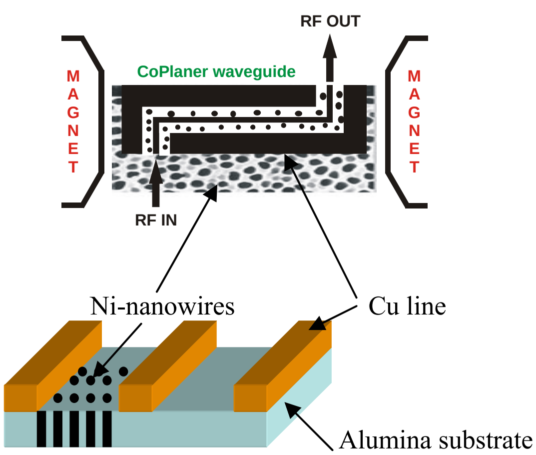

Figure 2: (Top) Design of Filter: Coplanar wave guide transmission line fabricated on top of the alumina template filled with Ni Nanowires. (Bottom) Design of Isolator: nanowires are only on one side of the gap between the signal line and the ground line of the alumina matrix.

The isolator is designed using the general ideas found in a waveguide-based E-plane resonance isolators. The positioning of the nanowires for maximum isolation is observed to be at one side of the gap between the central signal line and the ground line of the CPW. This is achieved by multiple photolithography and etching procedures. The device characterization was done using a vector network analyzer along with a micro-probe station. The frequency was swept from 0.05 to 70 GHz at zero or a fixed external magnetic field (H). Noise, delay due to uncompensated transmission lines connectors, its frequency dependence, and crosstalk which occurred in measurement data, have been taken into account by performing through-open-line (TOL) calibration using NIST Multical® software [9]. The width of the signal lines was 20 μm and the length of the device was 3 mm. The filters were designed for a 50 Ω characteristic impedance [10,11]. The exact resonance frequency (f_r) was obtained from the Lorentzian fits to the experimental transmission (S_{21}) data.

3 RESULTS AND DISCUSSIONS

Figure 3 shows the transmission response of the band-stop notch filter in the CPW geometry for 23 μm length nanowires at two different magnetic fields of 0.25 (red line) and 3.45 (black line) kOe applied perpendicular to the wire-axis. At the ferromagnetic resonance (FMR) frequency there is approximately ~ 6 dB absorption dip and a bandwidth of 6-7 GHz. The larger bandwidth is due to the shape anisotropy of the rods in comparison to the continuous film.

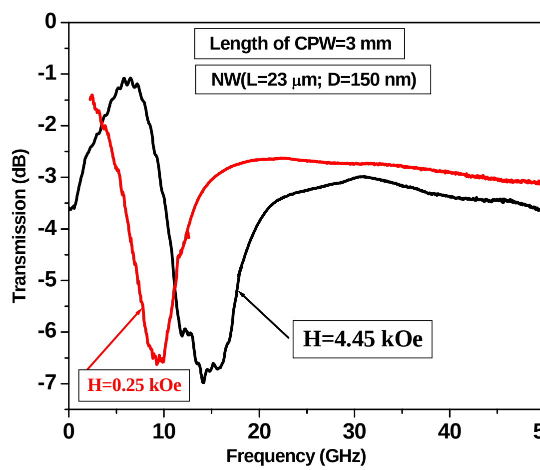

Figure 3: Transmission response measured using a network analyzer system versus frequency at two different magnetic fields applied perpendicular to the nanowires.

The resonance frequency versus magnetic field applied parallel and perpendicular to the nanowire-axis for this filter are shown in Figure 4. These stop-band effects are induced by gyromagnetic resonance phenomenon in the metallic nanowires. The effect occurs even in the absence of an applied dc magnetic field due to the shape anisotropy created by the wire geometry. The zero-field (or lowest field) f_r occurs at 10.5 GHz.

The stop-band frequency can be tuned by the application of magnetic field both in parallel and perpendicular configurations. But the behavior is different in the two cases. For perpendicular case, there are

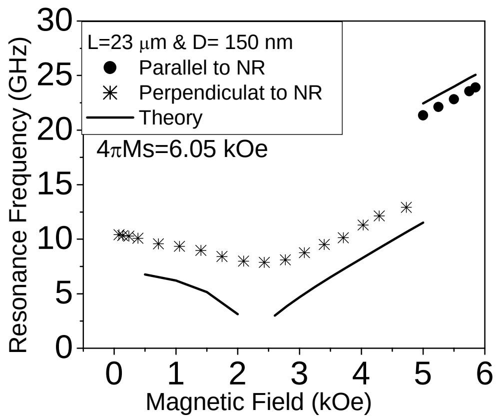

Figure 4: The band-stop notch frequencies versus dc magnetic field, H applied perpendicular (stars) and parallel (dots) to nanowires. The solid lines correspond to the theoretical fit.

two frequency-field regimes. The resonance frequency first decreases with the decrease of applied magnetic field down to a certain value. This point of deviation of frequency-field curve corresponds to the sample leaving its saturation state [6-7]. The kink in the f_r(H) data indicates the effective field (H_{eff}), occurs at ~ 2.4 kOe. This value is very close to the experimentally determined value of H_{eff} for the conventional FMR [12]. For the parallel geometry, the frequency increases with the increase of applied field, without a soft-mode like behavior.

To analyze the frequency-field data, the FMR condition [4] is considered - for an array of infinite single domain nanowires; for field perpendicular and parallel to the wire-axis. The relation for these cases reduced as follows [4, 7];

$$\left(\frac{\omega}{\gamma}\right)_{parallel} = \left(H + H_{eff}\right) \tag{1}$$

$$\left(\frac{\omega}{\gamma}\right)_{\perp} = \sqrt{\left(H_{eff}^2 - H^2\right)} \quad \text{where } H < H_{eff} \tag{2A}$$

$$\left(\frac{\omega}{\gamma}\right)_{\perp} = \sqrt{\left(H - H_{eff}\right)H} \quad \text{where } H > H_{eff} \tag{2B}$$

The eq. (1) corresponds to parallel geometry, when nanowires are parallel to the applied magnetic field. Eq. (2) corresponds to the f_r(H) data when the applied field is perpendicular to the nanowire axis. The eq. (2) has two parts - part (A) corresponds to the applied field value less than the effective field (H_{eff}) and part (B) corresponds to the field value greater than H_{eff}. To fit the f_r(H) data, the effective field (H_{eff}) and gyromagnetic ratio (γ) were used as fitting parameters and the value of $4\pi M_S = 6.05$ kOe (bulk value of Ni) was used. The solid lines in Figure 4 are evaluated from Eqs. (1) and (2). The H_{eff} values obtained from the experimental data increase with decreasing nanowire length (other nanowires not shown here). The H_{eff} values thus obtained are 2.24 and 1.33 kOe for 23 and 50 μm length filters, respectively. The effective gyromagnetic ratio γ'(=γ/2π) are 3.1 and 3.2 GHz/kOe for filters with the 23 μm 50 μm length wires, respectively. We note that the deviations of the experiment from the theory in Fig. 4 show that the nanowires are not in a saturated state over most of the fields examined.

Microwave resonance-isolators (non-reciprocal devices) are realized and measured by a vector network analyzer and a micro-probe system. An isolator is a 2-port device that allows power flow in one direction with little attenuation and a large attenuation in the reverse direction. The scattering matrix of an ideal 2-port isolator is given by:

$$S = \begin{vmatrix} S_{11}\, S_{12} \\ S_{21}\, S_{22} \end{vmatrix} = e^{j\theta} \begin{vmatrix} 0\,0 \\ 1\,0 \end{vmatrix} \tag{3}$$

In an ideal isolator both the ports (1 and 2) are matched, but transmission occurs only in the forward direction and the reverse transmission is blocked by 100%. In our case, the isolator is designed based on the principle of a waveguide based E-plane resonance isolator. Such a result is illustrated in Fig. 5. These isolators operate near the gyromagnetic resonance of the magnetic material.

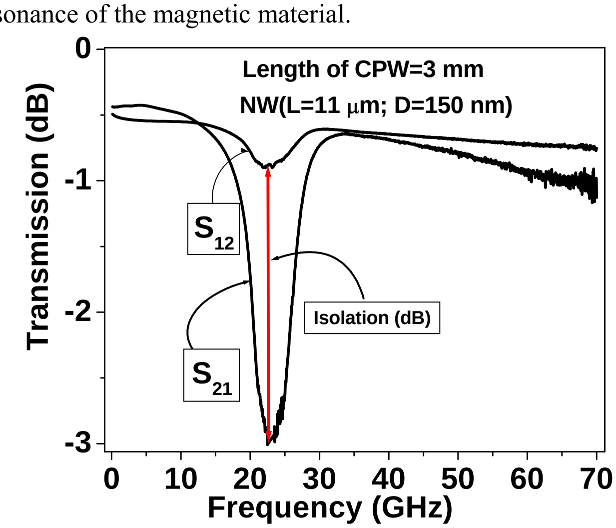

Figure 5: Transmission response measured by Network Analyzer system demonstrating the effect of isolation between port 1 and 2 of the device. The red line shows the level of isolation.

The attenuation of the wave (Fig. 5) propagating from Port 1 to 2 (S_{21}) is large at the gyromagnetic resonance of Ni, while in the return direction from Port 2 to 1 (S_{12}) the attenuation of the signal is very small. The difference between these two coefficients represents the efficiency of the isolator and must be as high as possible. Results on the transmission coefficients show a non-reciprocal effect, which reaches ~ 6.5 dB/cm at 24 GHz (Fig. 5). The bandwidth of the device is relatively large (5-7 GHz) in comparison to typical ferrite-based devices. The device can

NSTI-Nanotech 2008, www.nsti.org, ISBN 978-1-4200-8505-1 Vol. 3

operate over a wide frequency band (Fig.6) with application of an external magnetic field.

The nanowires are considered to be close to an infinite cylinder, because the diameter is very small in comparison to the length. For this geometry, the demagnetizing factor N_x is in a direction perpendicular to the wire axis and is taken as1/2. The FMR condition for an array of infinite single domain nanowires with field applied parallel to the wire-axis is given by eq. (1). The advantage of this geometry is that the full-height nanowire can be easy to bias by an external permanent magnet. The second advantage of our device is that it has a much broader bandwidth (~ 6 GHz), in comparison to ferrite-based isolators which have a bandwidth of a few hundred MHz. The bandwidth of the device is dictated primarily by the ferromagnetic resonance linewidth of the material, and Ni has a much larger linewidth in comparison to ferrites and garnets. The third advantage of the metallic based isolator over ferrite isolators is that it can be well suited for high power microwave applications. This is because the power-handling capability of a ferromagnetic metal [13] - like Ni - is much higher than YIG or spinel ferrites. The disadvantage of our device is the low value of stop-band rejection (~9 dB/cm). This can be improved by using a microstrip transmission line geometry instead of the coplanar one that is being used here.

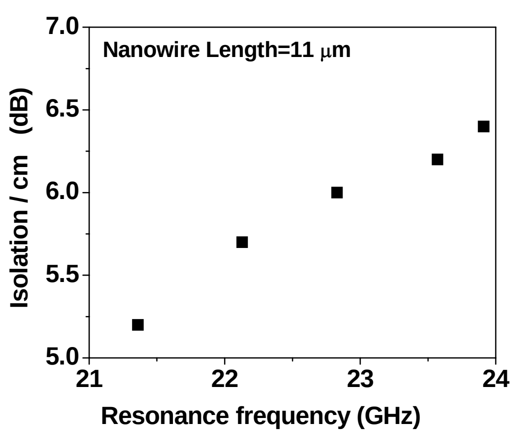

Figure 6: Observed isolation as a function of frequency for the nanowire based coplanar structure. The magnetic field is changed by about 1 kOe over this frequency range.

The performance of broadband isolators can be characterized by the ratio f_{max}/f_{min}, where f_{min} and f_{max} are defined as the edges of the frequency band in which the devices have acceptable operating characteristics. For the most advanced isolators available today this ratio is approximately 3:1. The measured broadband performance of our design is about 2.5:1. This does not represent any fundamental limitation on this ratio, but is due to the unavailability of a larger magnetic field in our laboratory. As the device under present study operates in a quasi-TEM mode, there is no cut-off frequency in the device. A much higher operating frequency (f_{max}) can be achieved by the use of a larger magnetic field. Furthermore the necessary applied fields will be lower than those used in ferrite isolators.

4. CONCLUSION

In summary, we designed, fabricated, and characterized reciprocal and non-reciprocal microwave planar devices using high aspect ratio Ni nanowires, fabricated by electro-deposition inside the pores of an alumina matrix. The field variation of the resonance frequency f_r(H) data provides a measure of the effective anisotropy field (H_{eff}) and the gyromagnetic ratio (γ). The isolation of the device reaches ~ 6.5 dB/cm at 24 GHz with a bandwidth of ~ 6 GHz.

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