and permittivity. A widely used example is a loop resonator, consisting of multiple coil turns and a discrete capacitor. Cummer *et al.* showed that the permeability of an array of loop resonators could produce a negative permeability. Intuitively, the resonators are operated past resonance, such that there is a significant out-of-phase component of the resonant current that creates a magnetic field that is opposite in direction to the incoming field. While promising, MM using passive components have proven very lossy, even with decades of advancement.

Active MMs have been an important area of research, however, the term “active” has been used for a wide array of phenomena. Most “active” MMs have a non-passive

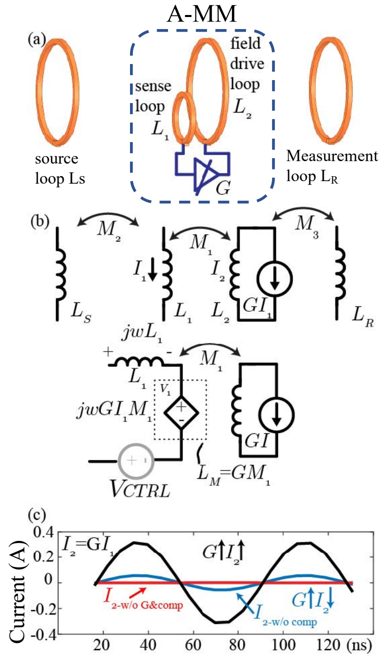

Fig. 1. (a) Example of A-MM cell. (b) Equivalent circuit model of single A-MM Cell. (c) Simulation results of a self-cancellation circuit.

component that is used primarily as a tuning element [5], [6] and did not address the loss of MM. Yuan [7] published one of the first (and only) works on an active MM that had sufficient gain to cancel loss, at one single permeability in the range of $0.5 < \mu < 1$. The challenge is in the coupling of the output of an active gain MM cell with the input and the resulting positive feedback loop. In addition, the output cannot swamp the input signal, for if it did, it would not be responsive to changes in the input signal amplitude and phase. In this work, we present an active MM cell for negative permeability applications that achieves a stable gain of 14 dB using a new self-interference cancellation method. This new approach should enable a wide range of future amplifying MM.

II. Theory

A conceptual diagram of our approach is shown in Fig. 1(a) & (b). The active magnetic metamaterials (A-MM) consist of a sense loop L_1 and a drive or output loop L_2. The input field is generated by a source loop and we measure the gain and phase caused by the A-MM with a receiver or measurement loop. As

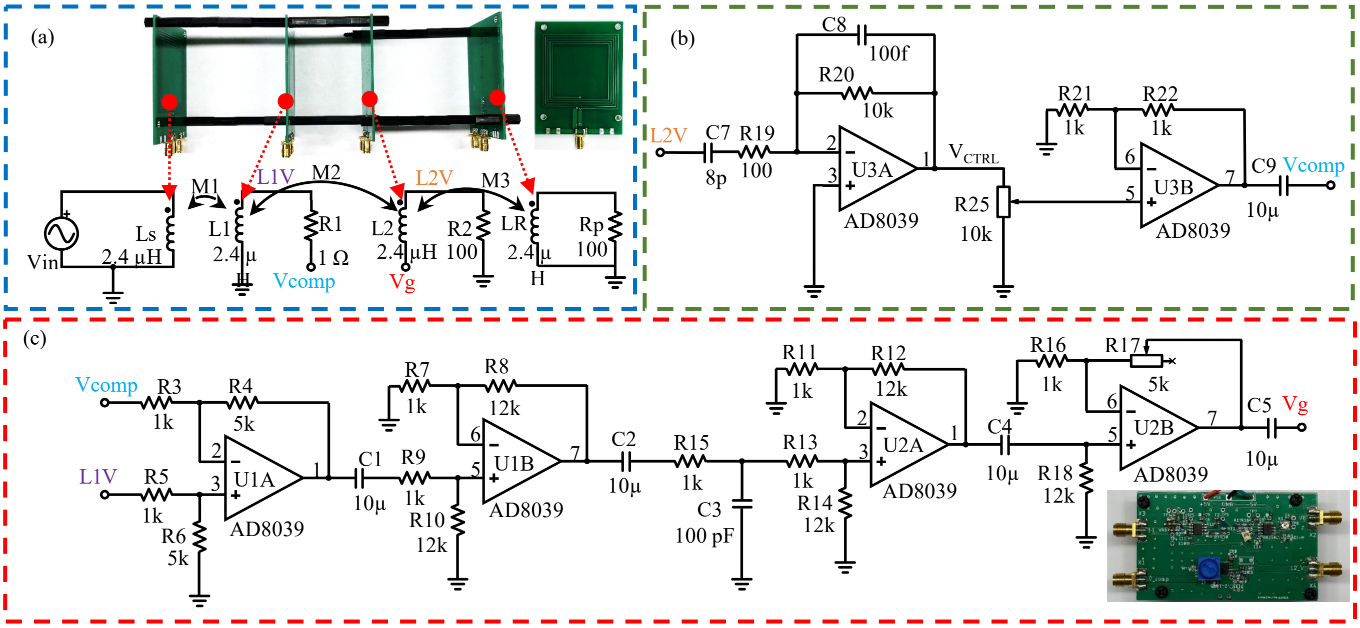

Fig. 2. The designed prototype and the circuit schematic. (a) The coils, (b) the compensation circuit, and (c) the gain stage.

the sense and output loops are close to one another, they have strong mutual coupling and any signal on the output is seen by the sense loop. To mitigate this self-coupling in the A-MM, we analyze the electromotive force (emf) V_1 generated by the coupling from L_2 to L_1. Figure 1(b) shows that I_2 induced the emf V_1 in L_1 that is 90 degrees out of phase with I_2 in L_2. This is significant, as the affect of L_2 is not in phase with the signal L_1 is sensing. Simulation shows that the phase shift causes not a positive feedback instability, but rather a gain degradation with stable operation. Our solution is to exactly cancel this emf in L_1 caused by L_2 by providing a cancellation voltage, V_{CTRL}, Fig. 1(b) bottom left. V_{CTRL} is connected in opposite polarity from the induced emf and is proportional to I_2 but with the required 90-degree phase (to be the same phase as the induced emf, which is 90 degrees out of phase from I_2).

Figure 1(c) shows the results of our approach. The black line is the desired outcome - an amplified stable sinusoid that tracks the phase[1] and amplitude of the input in a linear fashion. Without gain, the current in L_2 is very small. With gain, but the gain is much less than expected due to the induced emf. By providing the appropriate V_{CTRL}, the desired signal (black) is achieved.

III. Prototype Design

The designed prototype and schematic are shown in Fig. 2. It uses PCB coils for each loop or inductor. The operation frequency is 1.5 MHz, which has a wavelength much larger than the A-MM cell itself. As we are providing the amplification and gain, we did not use a resonator topology. The resonator (coil and discrete capacitor) used in prior works were to generate a phase shift and amplitude increase. With an active cell this is not needed.

The coils in Fig.2(a) were fabricated on FR4 boards (PCB). L_s and L_1 and L_2 and L_R are separated by 76.6 mm and L_1 and L_2 by 50 mm. The mutual inductance $M_1 = M_3 = 3.0343\ \mu H$, and $M_2 = 8.1341\ \mu H$. The gain stage and compensation circuit were made on a separate PCB, as shown in the photograph of Fig.2(c).

The compensation voltage V_{comp} is generated by a differentiator stage [U3A in Fig. 2(b)]. The current in L_2 is measured via $R2$ and injected into the compensation circuit. The circuit provides the required 90-degree phase shift. Its gain is controlled by the potentiometer $R25$ and is followed by a unity gain buffer. The measured V_{comp} lags I_{L_2} by 91.59° at 1.5 MHz, as measured by a vector network analyzer. As illustrated in Fig. 1(b), the emf V_1 leads I_2 by 90°. Therefore, there is an approximately 180° phase shift between V_{comp} and V_1.

The gain is achieved by measuring the current I_1 on $R1$ and using a 4-stage amplifier with filter as shown in Fig. 2(c). The total gain is 3600 V/V.

IV. Experiments

A. Compensation Mechanism Verification

We observed the current variations of the measurement coil before and after the compensation to determine the effectiveness of our proposed method.

First, we set a function generator output to 1.5 MHz sine wave with an (measured) output of 0.8 Vpp. The node 'V_{comp}' in Fig. 2(a) and (c) were connected to the ground to remove the compensation. To understand the interaction of each component, we first separated the sense and output coil so they were far apart. This allowed the sensing coil to measure

[1]By tracking phase we mean the phase difference does not change, such that if the phase of the input changes by 43° the output changes phase by 43°, even if the output has a fixed difference of 180°.

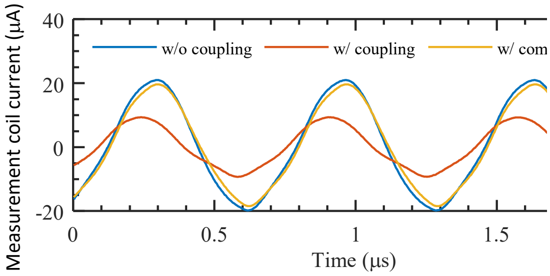

Fig. 3. The measurement coil current before and after comp

Gain

Phase difference i
Extra ~45 degree i

the input signal without the affect of the output coil. the output coil could produce the amplified curre interference from the sense coil. We used this meası determine the target measured current in our measure i.e. this is what would be measured if there were no or coupling between the sense and output coil. The peak-to-peak current of the measurement coil was 4 corresponding waveform is shown in the blue curves

Second, we placed L_1 and L_2 parallel to each 50 mm apart as shown in Fig.2(a). This was to m negative affects of the coupling (the compensation is off). In the orange curves of Fig.3, the measurement c has been reduced due to the mutual coupling betwe L_2 as described in the Theory section.

Third, we engaged the compensation circuit whi a voltage on the sensing coil L_1. As shown in the ye of Fig. 3, the current of the measurement coil almost to its previous value, which is 38.09 μA.

Overall, the compensation method reco measurement coil current and performed as expecte

B. Gain and Linearity

Key to the application of the A-MM to a N is the linearity of input to output. We, therefore, circuit to ensure the compensation and stability w with input voltage (and phase). The linearity of this single cell was examined by varying the source coil current. As shown in Fig. 4, the measurement coil current linearly changed with the source coil current, showing good linearity of this single cell.

Fig.5(a) shows the measurement coil current before and after turning on the cell. The cell generated a magnetic field that has a 224° phase difference than the incident field. The extra 44° was caused by the low-pass filter in the gain stage. The measurement coil current increased approximately 4.5 times in magnitude after the cell was turned on. Fig. 5(b) is the S_{21} measured from the source coil to the measurement coil before and after turning on the cell, showing that there is a 14.4 dB gain of our designed cell. Also, since the differentiator has a 90° phase shift over a range of frequencies, the A-MM produced stable gain over a large bandwidth.

V. Conclusion

This paper analyzed the self-coupling model of single A-MM cells and proposed a compensation method to eliminate the self-coupling effect. The designed prototype has a 14 dB gain and negative permeability. In future work, further analysis of the performance and stability will be conducted with different distances between the sensing coil and the output coil.

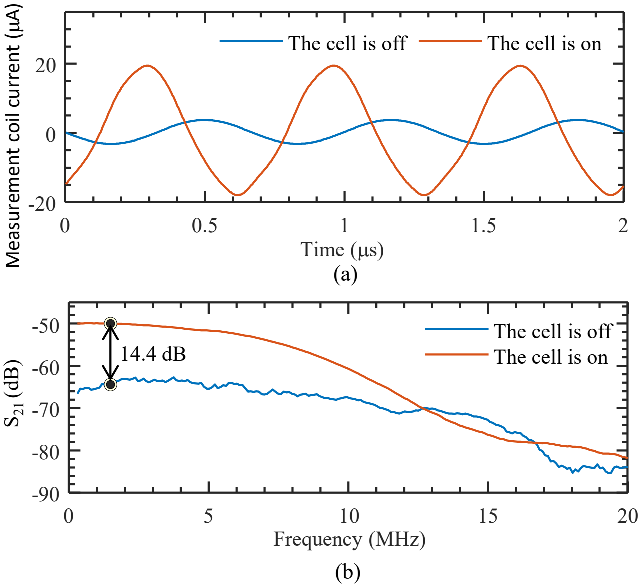

Fig. 5. (a) The measurement coil current and (b) the S_{21} before and after turning on the cell.

Acknowledgment

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