TUNEABLE META-MATERIAL SPLIT-RING RESONATORS FOR IMPEDANCE MATCHING ANTENNAS FOR BROADBAND APPLICATIONS

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ABSTRACT

In this paper, we present the design of a reconfigurable antenna based on the dynamic tuning of a planar system that consists of a loop antenna, metamaterial spilt ring resonators (SRRs), and heterojunction photo transistors (HPTs). Simulation results of a unit cell of SRRs indicate that the resonant frequency of the SRRs shifts from the original of 65 GHz to 76 GHz with a HPT introduced into the gap of the ring. In combining the SRRs and HPTs with a loop antenna, a tuneable antenna system is designed having a tuning range from 41.5 to 44 GHz. In addition to the ability to tune the planar antenna, it offers the advantage of being compact and easy to integrate, which ultimately reduces signature and offers more flexibility for army platforms.

1. INTRODUCTION

The development of tuneable antennas has attracted considerable interest in recent years because it offers the ability to combine multiple antennas operating at different frequencies into a single aperture antenna. From an Army perspective, one driving motivation is the limited space available for the placement of multiple antennas on various military platforms as well as the electromagnetic interference (EMI) that separate antennas create. In addition, there is also significant interest in reducing the physical size of antennas while preserving the frequency at which they operate. In all of the above cases, it becomes increasingly difficult to keep the antennas tuned to their receivers over wide bandwidths. In particular, this reduces to a problem of impedance matching the antenna assembly to the receiver system. Our approach to realizing a system capable of achieving wide bandwidth operation is to use meta-material devices that allow for the dynamic tuning of the antenna. To this end, we will show that multiple functionalities can be obtained by introducing meta-material split ring resonators (SRRs) as tuneable impedance devices for broad bandwidth antenna receivers. SRRs are subwavelength resonators with frequency-selective behaviours that serve to exhibit a tunable inductance by virtue of an induced current around its loop when at, or near, resonance [1-7]. To this end, SRRs have been used in the design of antennas in order to miniaturize antenna size while preserving its frequency of operation, by way of inductively loading the antenna.

Another important aspect of SRRs is their potential application to the design of reconfigurable structures, namely, electronically controlled or tuneable devices, such as very broad bandwidth antennas. In this application, we propose to demonstrate the tune ability of the SRRs, and thereby an electrically tuneable antenna, by using a transistor at the junction of the SRR. The transistor serves to change the local capacitance in the SRR, thus tuning its resonant frequency and, hence, its ability to inductively load an antenna. As a result, one can control the resonant frequency of the antenna as well as its output impedance, which can be used to ensure a very efficient and widely tuneable antenna system.

The schematic layout of the tuneable loop antenna with SRRs and transistors is shown in Fig. 1(a).

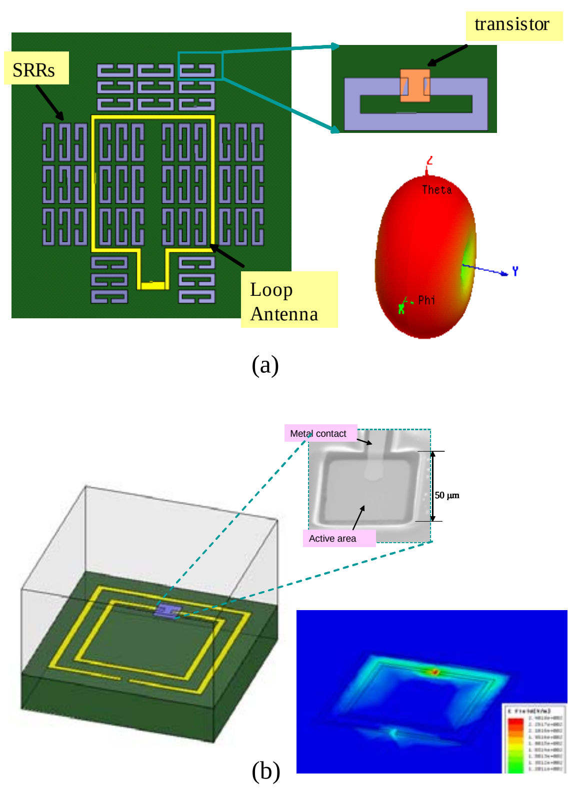

Figure 1. (a) SRRs and HPTs enabled tunable loop antenna and its radiation pattern, (b)tunable SRR unit cell with an embedded HPT and simulated E-field pattern using HFSS

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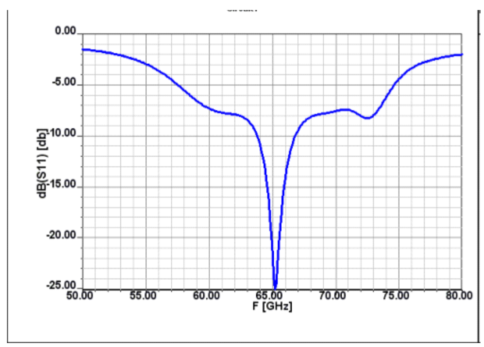
2. SRR UNIT CELL

To tune the resonant frequency of the antenna utilizing SRRs, our first step is to validate the tune-ability of the SRRs. SRRs are specially engineered micro-structured materials or metamaterials, which have been under significant investigation during recent years due to their intriguing properties such as negative refraction. Negative refraction of an SRR arises from its unique properties associated with the negative real parts of the magnetic permeability and dielectric permittivity. As such, it has been demonstrated that SRR systems possess macroscopic negative-index properties and, thus, exhibit peculiarities not found in natural materials. Most attention has been focused on the passive control and linear properties of these composite structures, where the effective parameters of the structure do not depend on the intensity of the applied field or propagating electromagnetic waves. However, dynamically controlling the material's properties in real time through either direct external tuning or nonlinear responses offers the opportunity to explore the full potential of the unique properties of the SRR. Because of the resonant nature of the SRRs, the microscopic electric field in the vicinity of the metallic particles can be much higher than the macroscopic electric field carried by the propagating wave. This provides a physical mechanism for dramatically enhancing nonlinear effects in left-handed materials.

As is well known, SRRs are resonant structures with resonant frequency $\omega = (LC)^{-1/2}$, in which C is the capacitance due to the gap and L is the inductance of the metal ring. There are many ways to alter their resonant frequency through an externally controlled element. One simple way is by altering the gap capacitance. In our design, we accomplish this by introducing a photo transistor in the gap of the ring. The variable capacitance of the transistor changes the capacitance of the SRR gap, which consequently alters the resonant frequency of the SRR.

The capacitance C(V) of a transistor comes from the depleted region of the junction. Under biases, the depletion region changes, which in turn affects the capacitance of the transistor. This way, variable capacitance is obtained by applying a bias voltage to the transistor, which in our case is a photo-transistor. We chose a photo-transistor in order to allow optical reconfiguration of a multi-functional antenna. To illustrate the tuning functionality, we designed and simulated a SRR unit cell using Ansoft HFSS, as shown in Fig.1 (b). The unit cell is a cube with PEC and PMC boundary conditions. A copper SRR on top of a Duriod substrate is placed inside the unit cell, which has PEC top and bottom walls and PMC sides. The selection of PEC and PMC boundaries in this unit cell is chosen to reflect the periodic nature of the SRR.

To evaluate the field inside the SRR, the structure is first simulated with a normal incident plane wave with E-field polarized along the gap of the SRR. The simulated E-field pattern at the frequency of 65 GHz is shown in Fig. 1(b). A maximum E-field pattern is located in the internal ring slit position, which is about 240 times that of the incident plane wave. We selected this position to place the HPT since the capacitance added by the HPT will produce a higher influence of the overall capacitance. Therefore, the HPT inserted to the gap of the inner ring will serve to effectively tune the resonant frequency of the SRR. Utilizing Ansoft Designer, we simulated the frequency responses of the SRR without and with the HPT in the gap. The resonance frequency of the SRR is observed via the frequency variation of the scattering parameter S11. From the simulation results, the resonant frequency of the unloaded SRR is around 65 GHz, as shown in Fig. 2 (a).



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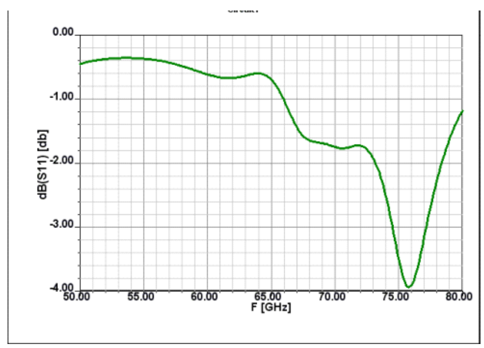


(b)

Figure 2. (a) Simulated S11 of the SRR without and with HPT using Ansoft HFSS and Designer simulators.

To analyze the tuning effect, we have introduced lumped ports at the internal ring gap location in the full-wave simulation. The HPT is introduced in these lumped ports in the following circuit simulation. With the HPT inserted in the gap area, the simulation results show that the initial resonance located at 65 GHz for the SRR has been shifted to 76 GHz, as shown in Fig. 2(b).

3. TUNALBE LOOP ANTENNA SYSTEM

Based on the tuneable SRRs, we have designed a tuneable loop antenna with SRRs and HPTs as tuning elements. The SRRs are designed in-plane with the loop antenna for the fabrication convenience. To simplify the fabrication process, the SRRs are modified to a single ring configuration as shown in Fig. 1(a). The SRRs are in-plane with the loop antenna for miniaturization and tuning of the antenna. The loop antenna is 2.4 mm × 2.6 mm with width of 0.16 mm. The dimension of the SRRs is 0.87 mm × 0.66 mm with width of 0.16 mm. The antenna and the SRRs are fabricated on a 30 mil-thick RT Duroid 5880 substrate with relative permittivity ε_r =2.2. Copper metallization is used to form both the antenna and SRRs. The HPTs are incorporated in the gap of the SRRs as well as the loop antenna for the tuning of the antenna. Ansoft HFSS and Designer are utilized to co-simulate the combined structure. Figure 1(a) shows the radiation pattern of the loop antenna with in-plane SRRs. As in the simulation of the SRRs, internal lumped ports are introduced in the Designer to simulate HPTs as voltage-controlled capacitances. The loop antenna and SRRs can be viewed as an open-ended microstrip line, which can serve as feeding probes. To electrically tune the circuit, bias is applied to the HPTs. Capacitors and chokes are introduced into the circuit to isolate the RF from the biasing parts of the circuit. Since the RF signal has very low amplitude as compared to the bias voltage across the HPT terminals, the entire system can be assumed as an equivalent 'small signal' situation. The variation of the bias voltage produces a variation on the resonance frequencies. This variation comes from the variable capacitances of the loop antenna and SRRs caused by the HPT load.

By applying different voltage values to bias the HPTs, their capacitances are varied and the influence on the resonant frequency of the combined structure is plotted in Fig. 3.

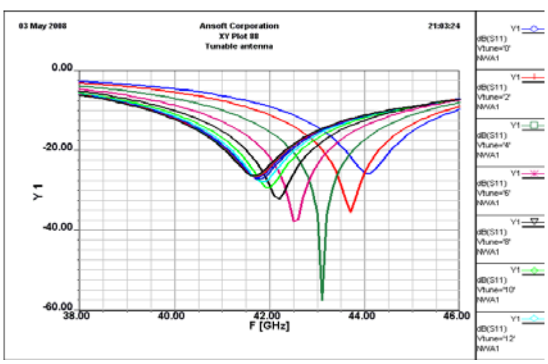


Figure 3. Simulated S11 of the tunable antenna with the HPT biased from 0 to 12 V using Ansoft Designer simulators

This graph shows that the tuning of the resonant frequency is performed from 41.5 to 44 GHz for the applied voltage varied from 0 to 12 V. An improved matching and hence decreased reflection as compared to the unloaded case is obtained by dynamically optimizing and matching the entire system. As a result, an approximately -60 dB reflection at the resonance frequency of 43 GHz is obtained. To experimentally validate the simulation results, we designed and fabricated the HPT.

4. FABRICATION OF HPTS

HPTs have been studied for the last several decades as a promising alternative to p-i-n photodiodes or avalanche photodiodes for optical communication systems. In our case, we utilize the advantage of the HPT, such as high gain, large dynamic range, low noise and low bias voltage for tuning the SRRs. Utilizing HPTs to tune the antenna also allows the optical control of the antenna. Among HPTs, AlGaAsSb/InGaAsSb quaternary material systems provide fabrication flexibility in tailoring the detection wavelength [8-10]. In addition, these HPTs can be optimized for a wide wavelength range with high internal gain, which leads to high responsivity and high signal noise ratio (SNR).

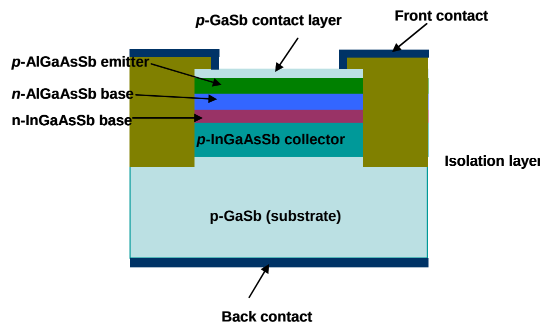
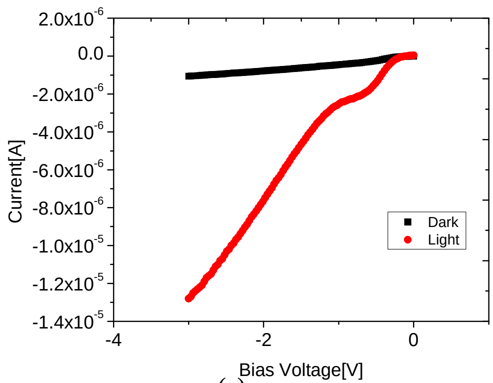


Figure 4. Schematic of the AlGaAsSb/InGaAsSb HPT structure

The AlGaAsSb/InGaAsSb HPT is a two-terminal device with a floating base. The active area of the device is 50×50 μm size. Base current is generated optically through the incident light. The p-n-p type device is designed with a p-type (4× $10^{17}cm^{-3}$) 0.3-μm-thick $Al_{0.4}Ga_{0.6}As_{0.14}Sb_{0.86}$ emitter, an n-type (6 × $10^{16}cm^{-3}$) 0.2-μm-thick $Al_{0.4}Ga_{0.6}As_{0.14}Sb_{0.86}$ and an n-type 0.5-μm $In_{0.16}Ga_{0.84}As_{0.14}Sb_{0.86}$ base, and a p-type (6 × $10^{16}cm^{-3}$) 1.5-μm-thick $In_{0.16}Ga_{0.84}As_{0.14}Sb_{0.86}$ collector. Heavily doped p-type (5×$10^{17}cm^{-3}$) GaSb is used as the substrate and as the contact at the emitter end. The HPTs were defined using photolithography and wet chemical etching. Gold was evaporated on both front and back side of the device by electron-beam evaporation to form Ohmic contacts for the emitter and collector. A polyimide PI-2723 manufactured by HD Microsystems was spun on the front surface of the device to serve as planarization of the top surface, mesa isolation, and edge passivation.

To characterize the device, A Hewlett Packard 4156B precision semiconductor parameter analyzer and a Hewlett Packard 4284A precision LCR meter are used. Figure 4(a) shows the I-V characteristics of the p-n-p type HPTs grown by molecular beam epitaxy (MBE) techniques under dark and light condition at 20°C. It shows a very low dark current, which is about 2 μA. The light current indicates the photo response of the device. The C-V curve shows that the capacitance of the HPT increases from 0 to 6 pF with the reverse bias voltage increase from 0 to 3 volts. These measurement results demonstrate the feasibility of the HPTs functioning as a tuneable capacitance to tune the resonant frequency of the antenna.



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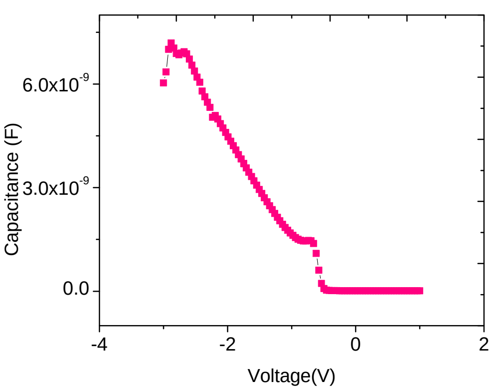

(b)

Figure 4. Measured (a) I-V and C-V curves of the fabricated HPTs

5. CONCLUSION

In conclusion, we present a novel design of meta-material based wideband tuneable antenna structure as both a transmitter and a receiver. The tune-ability is realized by incorporating HPTs into the SRRs and the antenna. Simulation results show that a tuning range from 65 to 75 GHz can be obtained with a SRR structure by adding the HPT to the inner ring of the SRR. In addition, we also showed that a tuning ranging from 42 to 44 GHz can be achieved by embedding SRRs and HPTs into a loop antenna structure. Furthermore, reflection as low as -60 dB is obtained by dynamically impedance matching the circuit.

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