Optically Pumped Reconfigurable Antenna Systems (OPRAS)

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Abstract

This paper presents a new reconfigurable antenna design using optical switching which overcomes any biasing associated with standard MEMs and PIN switches. In our approach, the switching elements comprises of doped silicon, and the change in the element's RF conductivity from that of a semiconductor material to that of a metal-like material is achieved upon exposure to a laser light coupled through an optical fiber cable. Two prototype antennas are fabricated and tested to demonstrate the proposed approach. Good qualitative agreement is observed between the simulated and measured data.

Introduction

The RF reconfigurability of a radiating structure (antenna) is of great interest in the field of wireless communications particularly for MIMO systems and cognitive radio applications. The basic concept of RF reconfigurability is to dynamically alter the physical structure of the antenna by connecting and/or disconnecting different parts of the antenna structure which interact with its radiation properties and thereby alters its RF response.

Recent research has explored the use of optical switches to fabricate reconfigurable antennas. In [1], the authors used an n-type silicon switch, doped with phosphorus, which was illuminated by a laser beam coupled laterally through an optical fiber. The authors implemented the photoconductive switch on a printed dipole antenna in order to create frequency/radiation pattern tuning. The switch has the effect of changing the dipole resonant arm length. An optically controlled frequency reconfigurable microstrip antenna was implemented in [2]. The authors used the idea of shortening the slot inside the antenna patch in order to change the electrical length of the RF surface current paths. This has the effect of producing a different resonant frequency. In [3], photoconductive switches have been used to model a fragmented bowtie antenna. The illumination of a small section of a variable conducting material using LED was discussed in [4].

In the approach described in this paper, a new geometry for coupling the laser light into the optical switch is explored and is applied to two different RF structures. The first design is a stripline fed circular patch. It achieves reconfigurability in the 11 GHz-13 GHz range. The second design is a modified polygon shaped CPW fed patch antenna. It performs frequency tuning in the 800 MHz-3.5 GHz range. In both design cases, the laser light is transversally coupled to the photoconductive switching elements by means of optical fibers. The optical fibers extend through holes drilled in the ground plane and the substrate. This type of illumination allows for conformal integration and better packaging of the optically switched antenna into commercial wireless devices.

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Photoconduction Models for Doped Silicon Switches

When light of appropriate wavelength falls on a semiconductor material, the energy of the photons is transferred to the valence electrons and elevates them to the conduction band. This increase of electrons in the conduction band produces a change in the physical properties of the material in terms of its dielectric constant, loss tangent and conductivity. The corresponding change in the dielectric constant is given by [5]:

$$\varepsilon_r = \varepsilon_L + \frac{ne^2}{m^* \varepsilon_o \left(-w^2 + j\frac{w}{\tau} \right)} \qquad (1)$$

n is the electrons or holes concentration (initial concentration 10^{15} cm^{-3})
q is the electron charge ($1.602*10^{-19}$ C)
m^* is the charge effective mass (kg)
w is the operating frequency (Hz)
τ is the collision time (10^{-3} sec)
ε_L is the dielectric constant of the silicon (11.9)

From equation (1), the physical properties of the silicon under different power levels can be derived [6]. This is summarized in Table I for f=12 GHz and f=1 GHz. It can be seen that as the carrier concentration increases, the conductivity of the silicon also increases and its dielectric constant decreases. However, the silicon becomes lossier due to the increase in its dielectric loss tangent.

Table 1: Physical Properties of the Silicon

f=12 GHz

Power Level (mW)	*Conductivity (S/m)*	*Loss Tangent*	*Dielectric Constant*
0	52	0.58	11.85
50	211	2.56	10.94
120	409	5.5	9.87
212	622	9.29	8.88

f=1 GHz

Power Level (mW)	*Conductivity (S/m)*	*Loss Tangent*	*Dielectric Constant*
0	52	7.07	11.85
50	211	30	10.92
120	409	66	9.86
212	643	116	8.77

Antenna Topologies

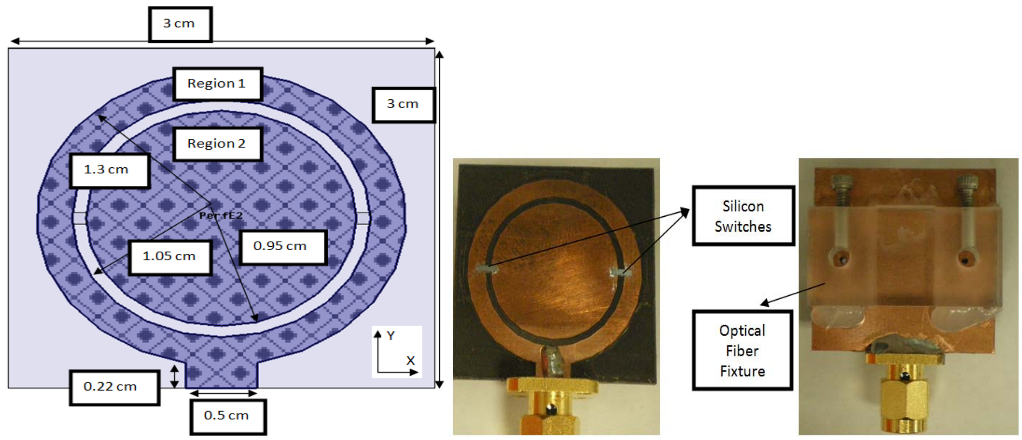
The first antenna structure consists of an outer circular annular ring (Region 1) and an inner circular patch (Region 2). Both structures are separated via a 1 mm gap and connected together via two silicon pieces that act as the RF switches. The dimensions of the different parts of the antenna structure are shown in Fig. 1(a). The top view of the fabricated antenna topology is shown in Fig. 1(b). The bottom view of the antenna structure is shown in Fig. 1(c). The chosen substrate is Rogers Duroid with a dielectric constant of 2.2 and a height of 1.6 mm. The light (808 nm laser diode) is delivered to the silicon switch via an optical fiber cable. It is placed underneath the substrate and held via a plastic fixture. To couple light into the silicon switch, two holes of radius 1mm each are drilled into the substrate, as shown in Fig. 1(c) and Fig. 2(c). The silicon switch used is 1 mm x 1 mm and has a thickness of 0.28 mm.

The second antenna structure is a CPW fed polygon shaped patch antenna. The antenna dimensions are shown in Fig. 2 (a). The top view of the fabricated antenna is shown in Fig. 2(b). The bottom view is illustrated in Fig. 2(c). The antenna substrate is Getek with a dielectric constant of 3.9 and height of 1.6 mm.

Results and Discussion

a) Stripline Fed Structure:

When the two silicon switches are OFF, i.e. not illuminated by a laser light, only the circular ring (region 1) is fed. This result in making the antenna resonates between 18 GHz and 19 GHz. Upon activation of the silicon switches, a new resonance begins to appear at 12 GHz. This is due to the mutual coupling between Region 1 and Region 2. Since the combined regions now represent an antenna with larger metalized surface area, the resonant frequency shifts lower. The simulated and the measured antenna returns loss for the different power levels are shown in Fig. 3(a) and Fig. 3(b). As the pumped power increases, the RF conductivity of the silicon switch increases thereby reducing the impedance mismatch between Region 1 and Region 2; and subsequently yields deeper resonances. By comparing both plots, one can observe a good qualitative agreement between the simulated and the measured data in terms of the frequency dependence of the observed resonances.

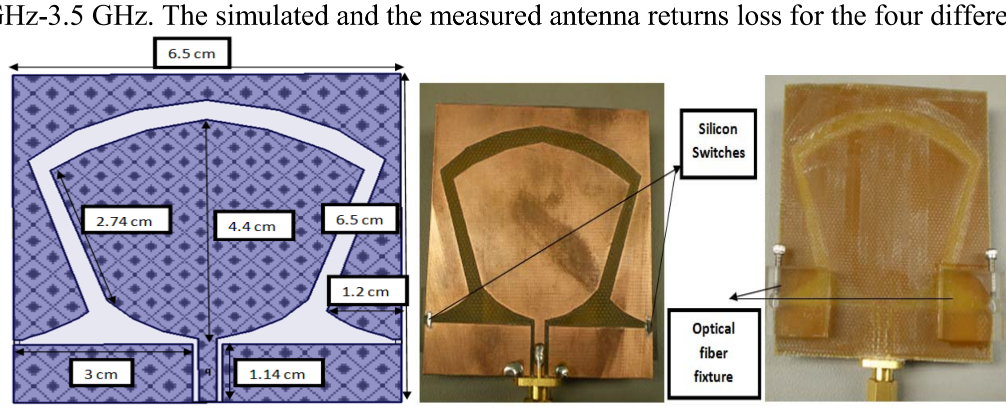


(a) (b) (c)

Fig. 1. (a) The stripline fed antenna structure (b) The antenna prototype in top view (c) The antenna prototype in bottom view

b) CPW Fed Antenna:

When both switches are OFF, i.e. not illuminated by a laser light, the antenna ground has a rectangular form on each side of the feed line. This makes the antenna resonate from 800 MHz-3.5 GHz. By activating both switches, the shape of the antenna ground changes. This has the effect of making the antenna cover the frequency band from 1.6 GHz-3.5 GHz. The simulated and the measured antenna returns loss for the four different



(a) (b) (c)

Fig. 2. (a) The CPW fed antenna structure (b) The fabricated prototype in top view (c) The antenna prototype in bottom view

power levels are summarized in Fig. 3(c) and Fig. 3(d). Good qualitative agreement is observed between the simulation and the measurement data.

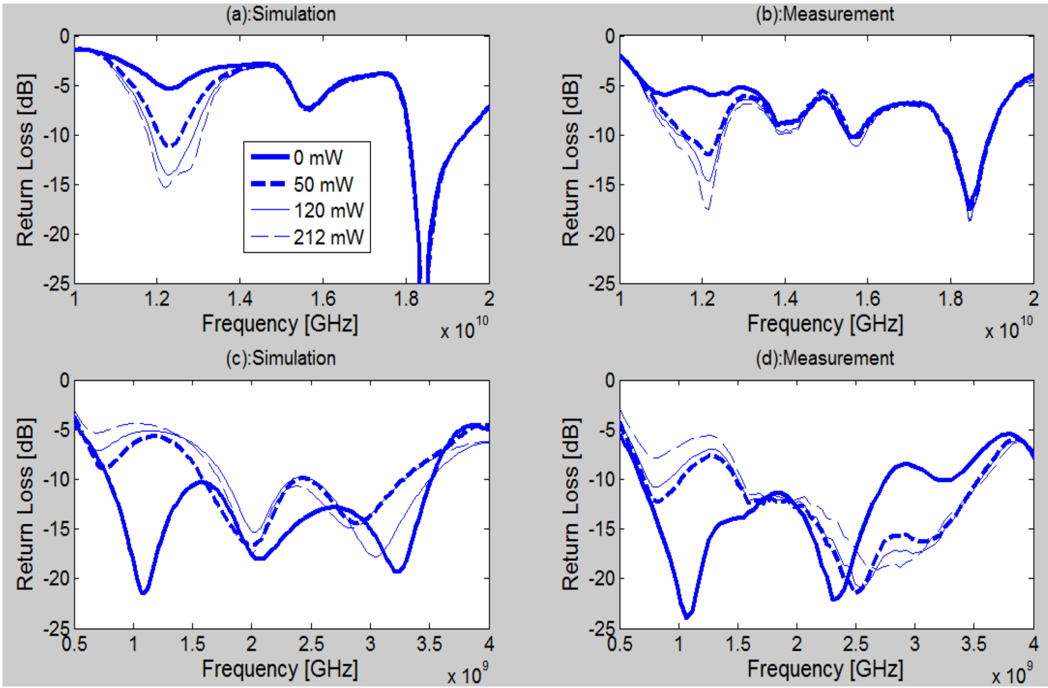


Fig. 3. Simulated/Measured Return loss for the stripline fed antenna (a/b) and the CPW fed antenna (c/d) for different incident laser levels

Conclusion

This paper presents a new approach to couple laser light energy into an optically reconfigurable antenna design using semiconductor switches. Good qualitative agreement is observed between the simulated and the measured data. The choices of the frequency ranges in this paper are arbitrary and serve to only validate the proof-of-concept for our approach. Our antenna designs can be easily refined to include frequency bands corresponding to established wireless standards such as GSM, CDMA, WiMAX, etc. For future work, one can explore methods to decrease the required pumped laser power by decreasing the dimension of the silicon switches and/or investigating other materials with faster switching speeds for transitioning between the semiconductive to metal-like states.

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