The Active Way of Tunable Frequency Selective surfaces

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***Abstract*—Frequency selective surfaces(FSS) is a topic of several decades and still attracting interests of researchers in many areas. Variation of FSS have been studied by many groups for different applications. Whatever, FSS worked with various types of sources have been paid much more attention for its tenability in frequency, bandwidth, and so on. In this paper, state of the art on tunable FSS with active stimulations was reviewed.**

***Keywords*—Active FSS, tunable, diode, mems**

I. Introduction

Frequency selective surfaces(FSS) have been an attractive topic for several decades for its widely usages in areas such as bandpass radomes[1-3], absorbers[4-6], dual reflectors for antennas[7-9] and even in new fields such as WLANs[10,11]. Most of these application take advantage of the bandpass or bandstop properties of a FSS structure. However, the traditional FSS(or named passive FSS) has fixed work frequency and bandwidth, which restrict the widely application of FSS. Meanwhile, if the parameters of the FSS varied, the response of the FSS will change. For example, the frequency response of the simple unit of a ring with a dielectric substrate shown in Fig.1, will change with the variation of the width of the ring (see Fig.2). In this sample, the inner radius of the ring was 2mm, and the width of the ring realized by change the outer radius of the ring, it is shown from the figure that the peak of the frequency curves varies with the radius, with intentionally designing, which can be used to adapt to a situation of changing frequency. Thus, dynamically change on response of FSS raises the new line of adapted system.

With the motivation of dynamically use of FSS, the idea of tunable FSS was proposed, the first idea of loaded FSS with active method maybe traced back to 1980s then Ramakrishna Janaswamy and Shung-wu Lee of UIUC studied the scattering from dipoles loaded by diode[12]. The characteristic of a tunable are that the working frequency and band adjusted by changing size using MEMS[13,14], loaded devices like diode[15], using other materials such as liquid crystal[16], plasma[17-19], etc.

It is obviously that most of the tunable method of FSS are based on the actively way of parameter control, it is also benefit for the smart control of the FSS, and furthermore, the idea of smart absorber was proposed[20].

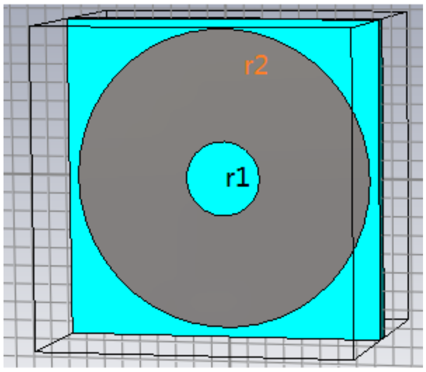

Fig. 1 the simple ring unit, when changing the width, the transmission peak will vary.

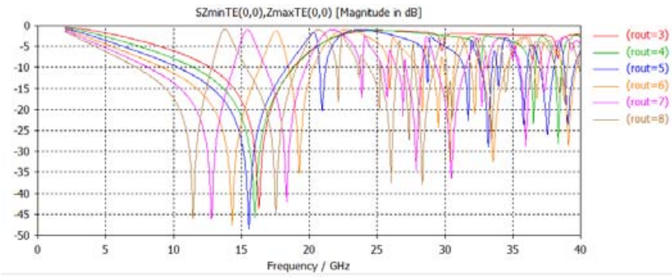

Fig. 2 variation in transmission with increasing of ring width from 1mm(rout=3) to 6mm(rout=8)

II. Types and Characteristics of tunable FSS

As descripted above, there are several ways including using plasma, semiconductor devices, MEMS, or liquid crystal to tune FSS for change its bandpass/bandstop frequency or to switch its transmission or reflection properties. On this aspect, the study of tunable FSS was motivated by widely applications, such as wideband absorber[21,22], smart absorber[20,23,24], smart antenna[25], smart radome[26,27], and even for Reconfigurable Electromagnetic Architecture of Buildings[28,29], and with more interests focused on radar absorbers and radar cross section(RCS) reduction.

A. *Semiconductor devices*

Using some semiconductor devices to tune FSS maybe the earliest method proposed. Semiconductor devices such as diode has the properties of switching under a special bias voltage, i.e., when it is biased positively to a threshold voltage, the diode will be in an on-state which allows the current to flow in it, while when negatively biased bellow the value of breakdown voltage, it will be in an off-state and plays as an insulator. In the range from negative biased to threshold voltage, the current varies nonlinearly with the voltage applied, indicating a nonlinear resistance zone. After that, the voltage-current curve will be in the linear zone, as shown in Fig. 3. Janaswamy and Lee proposed an idea in 1988 to tune the scattering form a dipole[12], which maybe the first idea to tune the scattering of a FSS like structure. Even earlier than this, Heuven[30] studied the use of PIN diode for phase shifter of electronically scanned aerial arrays, and they also showed the equivalent circuit of the PIN diode in on (left of Fig. 4) and off(right of Fig. 4)state, which can be used for analysis of the condition of the PIN diode loaded FSS.

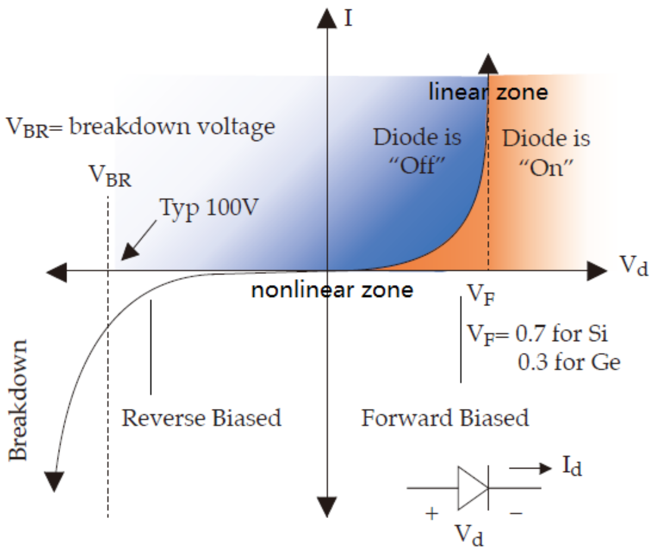

Fig. 3 the current-voltage curve and resistance zone (from[31] with some modification)

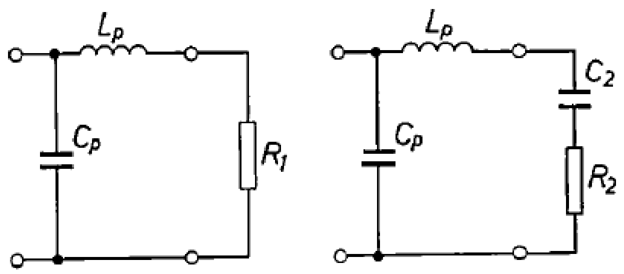

Fig. 4 the equivalent circuit of PIN diode with on-state(left), and off-state(right) [30]

There are several types of diode available for tuning FSS, and the ones used commonly by the researchers are PIN diode and varactor. Costa et. al[32] studied transmission and reflection properties with the loaded parameters variation for absorber application of FSS, with his simulation, it is shown that varactor-loaded absorber comprised of a patch FSS on a thin (0.8 mm) FR4-grounded substrate play different rules with the variation of capacitance of varactor and resistance of PIN diode. David Cure et. al. studied Non-Uniform Bias Enhancement of varactor for Low Profile 2.4 GHz Dipole Antenna to dynamically adjust the center frequency and vary the impedance match of the antenna to create broadband or multi-resonance responses[33].

B. *plasma*

Plasma is a special dielectric with its properties based on collective of ionized electrons, and shows some different properties from other dielectric. The most important parameter in plasma is electron density, which together with collisional frequency determines the behavior of electromagnetic wave in plasma. As a dielectric , the complex permittivity of plasma was determined by plasma frequency ω_p, the frequency of the wave impinging on plasma ω, and the collisional frequency mainly between electrons and neutral particles v, as shown in the following[34]:

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega(\omega - iv)} = 1 - \frac{\omega_p^2}{(\omega^2 + v^2)} - \frac{i\omega_p^2 v}{\omega(\omega^2 + v^2)} \tag{1}$$

It indicate in the equation that when plasma frequency for a non-collision plasma is larger than the frequency of the impinging wave, the permittivity will be negative, means that the wave can't transmit in the plasma. In addition, as the permittivity is also based on the incident electromagnetic wave , plasma behaves different from general materials. For an non-uniform plasma, the electron density varies with positions such as decreased from the center of the source to the outer areas, so there may be reflection, absorption and refraction in plasma, which means the change of electromagnetic wave when travelling in plasma. The second properties of plasma is that it is ionized gas, and can be switched very quickly, and thus can be used to dynamically control the behavior of electromagnetic wave in it.

Anderson[18] proceeded studies on Plasma FSS Radomes for Electronic Protection for Space-borne Phased Array Antennas under the project of SBIR, W. C. Lee studies the properties of crossed plasma FSS unit both by simulation and by experiments, showing good on/off results of the plasma tuning FSS.

C. *MEMS*

MEMS is the acronyms of Micro-electro-mechanical systems, and it is a type of switch devices under electric-mechanical effects of some devices. The piezo-electric materials on the bridge in the system will act as switch under the electric power applied. Kiani et. al. [13] studied 60 GHz FSS Modulator using MEMS as switches between elements, and got significant on and off state transmission results. Mojtaba Safari et. al.[35] studied X-Band Tunable Frequency Selective Surface with MEMS Capacitive Loads, shows that the reflection frequency vary discretely with the slot length changing with 1mm step, which is controlled by a the MEMS bridge, means that it can be adjusted to change of working frequency.. So, MEMS can be used for turn on /off the FSS or tuning its working frequency.

D. Liquid crystal and others methods

Besides the main methods of diodes, plasma and MEMS, several groups even studied other types of tuning FSS, such as liquid crystal, water, and materials with phase transition. Varittha Sanphuang et. al. [36] studied the use of phase transition material VO_2 films in reconfigurable frequency selective surfaces, and got good on and off state. P. Yaghmaee[37] studied liquid crystal for tunable FSS systematically in his Ph. D thesis. Dong Chan Son et. al.[38] tried to tune FSS using Fluidic Channels, and did some experiments.

III. PROPERTIES OF PIN DIODE TUNING FSS

Tuning of FSS with PIN diodes was mainly used for radar absorber design and adaptive radome design, which means that for the former, there is a metal background behind the FSS and substrate layer, while for the latter there is only the FSS structure of FSS unit layer and substrate layer, as shown schematically in Fig. 5. We think about it as an absorber first.

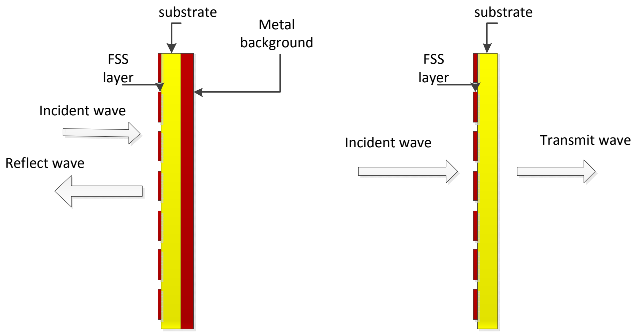

Fig. 5 the schematic of FSS with and without a metal background , for absorber and radome application respectively.

The papers focused on tuning with PIN diode are largely about how to use it as a radar absorber to enhance the reflectivity of the original structure. Group of Chambers [23,24,39] suggested a structure with PIN diode loaded to acquire the wideband minimum reflectivity, and they even use high frequency signal to modulate the so call phase-switched screen[40].

In fact, for a single layer, the equivalent circuit of PIN loaded FSS can be derived from that for a passive FSS or Salisbury radar absorber, as shown in Fig. 6, the C_T , L_T represent the capacitance and reactance of the structure, and C_{sa} , L_{sa} and R_{sa} represent the capacitance, reactance and resistance of the diode, respectively. Of course, in this model, the loss or resistance of the structure(can be expressed by R_T) was omitted as considering it as a lossless structure.

Simulation based on full wave method was conducted for a bow-tie structure. The schematic structure and simulated results of both without a diode and with a PIN diode were shown in Fig. 7-Fig. 12. It is shown from these simulation results that the reflection frequency depends on the size of the unit cell, and when loaded with diode, both the capacitance and resistance of the diode will contribute to the matching frequency of the structure. Although some authors [32] have reported the significant effect of capacitance on the reflection frequency, it plays weak role when the capacitance is very large. In addition, it can be found from the simulation results that, even without considering the contribution of the structure, the ultimate results are determined by the compensation of both resistance and capacitance. In Fig. 11, although capacitance varies in a very small range limited in one order below pF, the reflection peaks change only in a small range when the resistance is 50Ω, while when raise the resistance to 500Ω, there shows obviously change even in 2GHz bandwidth. In fact, if we set -15dB as the reflection baseline, it indicated that the reflection properties of the FSS structure can be tuned continuously among the 2GHz bandwidth, although the individual peak is somewhat narrow.

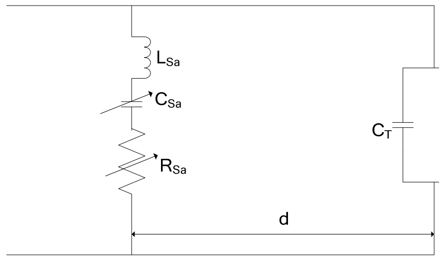

Fig. 6 the equivalent circuit of a PIN diode tuning single layer FSS

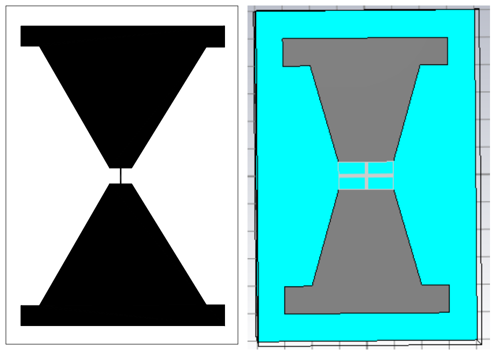

Fig. 7 the structure of unloaded (left) and loaded(right) single layer bow-tie FSS with metal background

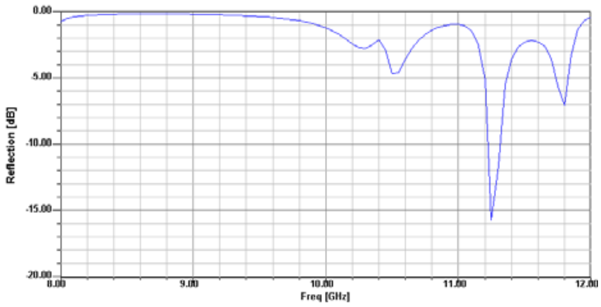

Fig. 8 the simulation results of the unloaded single layer bow-tie FSS.

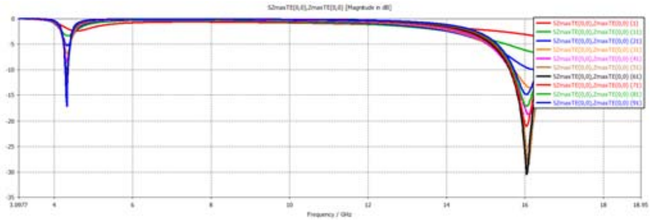

Fig. 9 the simulation results of PIN loaded tunable FSS with variation of the capacitance of the diode from 0.01pF to 0.01F while keeping the resistance at 50Ω.

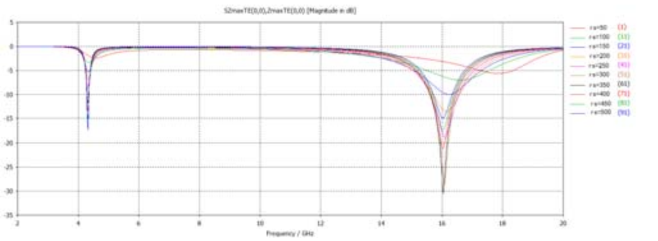

Fig. 10 the simulation results of PIN loaded tunable FSS with variation of the resistance of the diode from 50Ω to 500 Ω while keeping the capacitance of the diode at 0.01pF

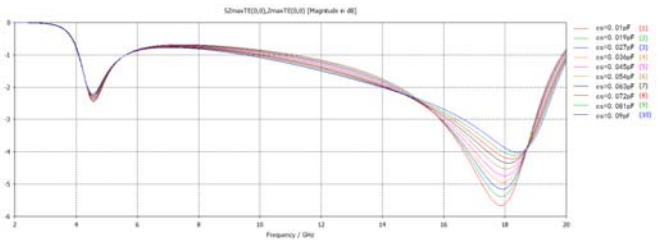

Fig. 11 the simulation results of PIN loaded tunable FSS with variation of the capacitance of the diode from 0.01pF to 0.09pF while keeping the resistance at 50Ω.

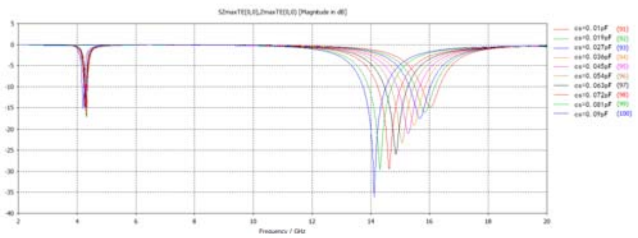

Fig. 12 the simulation results of PIN loaded tunable FSS with variation of the capacitance of the diode from 0.01pF to 0.09pF while keeping the resistance at 500Ω.

IV. SUMMARY AND CONCLUSION

It is reviewed in this paper the methods of tuning FSS with active way such as using semiconductor devices to load the FSS, using plasma unit cell and using MEMS to switch the FSS, and even ,using liquid crystal or liquid flow to modulate the properties from topics of radar absorber, smart radome, and adaptive frequency for other electromagnetic applications. In addition, two types of the unit loaded with PIN diode were modeled and simulated. It was shown from the results that both the size of the unit cell and the parameter of the diode contributed to the tuning properties of the FSS, there needs compensation among these parameters.

ACKNOWLEDGMENT

Shengjun Zhang thanks Dr. Fillipo Costa and Professor Agostino Monorchio of University of Pisa for the helpful discussion on FSS, and he also thanks Professor Wei Shao of University of Electronic Science & Technology of China for the help on work of loaded FSS, and he would also express thanks to Professor Min Zhang of softwave Ltd. for his help on simulation with CST microwave suite software.

This work was sponsored by National Science Foundation of China(NSFC) with number 61571031.

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