RESEARCH ARTICLE

Frequency Agile Slot Antenna Using Contactless Capacitive Loading

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ABSTRACT In this paper, a reconfigurable slot antenna capable of tuning a full octave in frequency from 2 GHz to 4 GHz is presented. The design is based on changing the capacitive loading of a slot antenna by physically displacing a metal plate connected to a piezoelectric linear actuator that changes the apparent electrical length of the antenna. The antenna was simulated, fabricated, and measured to tune across the 2-4 GHz frequency range while maintaining a maximum return loss of greater than 9.0 dB. Simulations also show a 65.74% to 95.75% radiation efficiency across S-band. A broadside realized gain of greater than 1.73 dB was measured over the entire tuning range. Moreover, the tuning mechanism was proven robust above other methods by withstanding up to 100 W of power incident on the feed at 3 GHz.

INDEX TERMS Slot antennas, tunable antennas, high-power antennas.

I. INTRODUCTION

Modern RF systems must deal with increasingly dense and crowded spectral activity. Broadband antennas cascaded with switchable filter banks have been the classic solution to this problem, but offer lower noise figure performance than a narrowband antenna with the same frequency response [1]. However, narrowband antennas make it difficult to scan over a wide range. Also, if a large noise source or jammer exists in band, both systems function sub-optimally. A tunable narrow-band antenna solves many of these problems, offering good noise figure performance with the ability to operate over a large band.

There has been much research on reconfigurable antenna designs, with many focusing on adaptive antenna loading as a tuning mechanism. Common loading mechanisms include varactors [2], [3], microelectromechanical systems (MEMS) [4], [5], and pin diodes [6], [7], [8] as well as ferroelectrics [9], [10], [11]. While these systems offer many benefits when it comes to reliability, incorporation into current PCB design processes, size, and weight, they suffer in one key region: power handling. Their physical properties cause serious limitations due to breakdown and undesirable non-linear effects [12]. These effects have limited the adoption of these highly adaptive antennas in high power applications like radar. Next generation systems need to operate in narrow frequency bands without risking spectrum pollution due to non-linearities. These problems can be solved with mechanical actuation of metal as a tuning mechanism.

Tuning using movement of metal has been around since the earliest days of radio [13]. It has been reliably used in systems such as old radios, radars, and telecommunications equipment. Static mechanical tuning is currently commonplace in microwave components, such as using screws for fine tuning of cavity filters [1]. Active, electrically controlled,
mechanical tuning is a relatively recent addition to the higher frequency domain of microwave components. Work has largely focused on the use of piezoelectric discs or rotating cam shafts with stepper motors as a movement mechanism. Both offer precise control of movement, power handling, and spurious frequency rejection benefits [14], [15], [16], [17]. Unfortunately, cam shaft actuation requires complex construction and, for antenna applications, requires large rotating pieces directly over the antenna. The piezoelectric discs have a fairly small deflection distance and are therefore limited to high loading applications to cause large changes in capacitance. The piezoelectric material and the nickel alloy they are coated in is also lossy, preventing their effective use in areas of high field density without serious impacts on efficiency due to ohmic losses.

Recent advancements in piezoelectric actuators, which use multiple piezoelectric crystals stacked up, have partially solved these problems. They allow for comparable degrees of control to piezoelectric discs but with much greater deflection distances. Of particular interest for this project is the M3-L Micro Linear Actuator by New Scale Technologies. This device can move up to 6 mm along an axis in 0.5 µm steps, allowing for much larger deflection than is possible with a single piezoelectric disc while maintaining precise control. The actuator has been used to achieve contactless tuning in frequency reconfigurable filters [18], [19], [20], and for impedance matching networks [21]. For antennas, another key aspect is that the actuator itself is far away from the aperture, distancing it from the strongest fields and thereby reducing impact on the antenna radiation properties.

In this paper, a tunable antenna is introduced that can tune a full octave, in this case across all of S-band (2-4 GHz), while maintaining high efficiency. A capacitive plate is positioned above a slot antenna, acting as two tunable capacitors in series in a shunt configuration. Displacing the plate changes the capacitive load seen by the antenna, causing the antenna to appear electrically larger or smaller. A series of capacitor plate geometries were examined for simplicity and efficiency, and a circular capacitive plate was chosen for its high efficiency, sensitivity, high-power handling, and resistance to positional error. A prototype design was simulated, fabricated, and measured to demonstrate the feasibility of such antennas.

**II. PIEZOELECTRIC ACTUATOR ANTENNA DESIGN**

One of the first choices when creating a tunable antenna is what type of radiating structure to use. Slot antennas offer a planar nature, low manufacturing complexity, desirable radiation patterns, and efficient operation. Slot antennas also offer a key benefit: they can be made as a single layer. Shunt components can be placed directly on the antenna without having to connect through a substrate, making the addition of tunability a simpler process [2].

There are several factors to consider when designing a tunable capacitively loaded slot antenna. One of the main concerns with this antenna is the ability to handle high power. To maximize power handling, the minimum capacitive gap needs to be as large as possible to limit dielectric breakdown, but this comes with a few drawbacks. As one increases the minimum capacitive gap, the area of the capacitive plate must increase to give an equivalent amount of loading. A large metal plate above a slot antenna causes undesirable interference in the radiation pattern. The large plate also forms a less sensitive capacitor as a larger portion of the plate is farther from the center, which is the location of strongest E-field.

The second main factor is tunability. A highly loaded slot antenna is much easier to tune than a lightly loaded one, as comparative changes in capacitance are much more easily achieved with small distances of movement. However, more loading makes the antenna electrically smaller as compared to its operational frequency, which consequently results in more loss [22]. Therefore, a balance between amount of loading, efficiency, tunable range, and power handling must be met.

To achieve a full octave of frequency tuning, the loading capacitance needs to change by a factor of four [23]. The approximate relationships for capacitance and their relationship to antenna tuning range was explored using ANSYS HFSS with the geometry seen in Figure 1. The capacitive gap was tuned from 10 µm to 40 µm, resulting in a resonant frequency change from 1.87 GHz to 3.02 GHz. The range is less than the octave predicted by above-mentioned assumptions, but the discrepancy can be attributed to fringing capacitance as well as the metal plate adding inductive loading that lowers the resonant frequency. Conveniently, given a starting distance of 10 µm, the piezoelectric actuator can quadruple the distance four times, making an octave of tuning well within the possibility of the actuator.

The main body of the piezoelectric actuator is a large metal box. There were concerns on what effect putting a large metal box above an antenna would have on its radiation pattern, loading, and efficiency. To see what effect these structures have, a simulated model with a mounting structure for the piezoelectric actuator, a simplified piezoelectric actuator, and feeding structure was created in HFSS. A Dyson balun [24] was chosen to feed the slot due to its reliable and simple manufacture. It was necessary to put the feeding point close to the end of the slot to ensure a good impedance match. The resulting model is seen in Figure 2.

The actuator mechanism reduced the tuning range of the antenna. To compensate for this reduction in tuning range,
the actuation distance was increased to tune from 2-4 GHz, shown in Figure 3. The final expected actuation distance was 15 µm to 245 µm. The maximum return loss across the entire tuning range was in excess of 12 dB with the structure, only slightly reduced from 13 dB with no structure. The simulated radiation efficiency of the antenna with the actuators structure ranged from 65.74% at the lowest frequency of the tuning range to 95.75% at the highest frequency. The radiation efficiency as a function of frequency is seen in Figure 4.

Figure 5 shows a comparison of the simulated slot antenna with the structure to support the tuning mechanism versus a floating plate without support moving above the slot antenna, and as can be seen in the figure the radiation pattern remained consistent across frequency as the antenna tuned and with the inclusion of the tuning structure. The broadside gain remained above 1.81 dBi for all frequencies measured. The minimum broadside gain decreased 1 dBi compared to the minimum of 2.70 dBi with no structure. The gain shown does not include mismatch loss. In summary, the structure has some effects on the performance of the antenna, but the effects were small or manageable. The design still functions acceptably for its intended use.

III. PIEZOELECTRIC ACTUATOR ANTENNA FABRICATION
A prototype antenna was fabricated to validate the simulation results. The slot was etched in the top layer of a copper-clad 125-mil-thick TMM3 substrate from the Rogers Corporation using in-house photolithography. The balun was positioned to feed the slot and then soldered into place. The mount for the piezoelectric actuator was 3D printed using a Stereolithography (SLA) resin printer. The piezoelectric linear actuator
was fixed into place in the printed mount. The mount was then attached to the slot antenna to complete the bulk of the fabricated structure. The capacitive plate used for tuning the antenna was cut from a copper-clad 60-mil-thick RO4350B substrate using a LPKF ProtoMat S103 circuit board plotter. Of particular sensitivity for the design is the mounting of the capacitive plate onto the piezoelectric linear actuator. Since the tuning changes significantly on the micrometer scale, a small departure from a perfectly parallel plate could result in different tuning performance. Great care was taken in mounting, where the plate was placed on the ground plane to ensure a parallel plate, then glue applied to the back. The piezoelectric linear actuator was slowly lowered into the glue and allowed to set. This approach allowed for a better starting vertical position, but alignment of the plate on the slot horizontally is not guaranteed to be perfect. A fully assembled version of the antenna and tuning structure is seen in Figure 6.

IV. EXPERIMENTAL RESULTS

After fabrication, tunability testing was performed by measuring $S_{11}$ with an Agilent Technologies N5225A PNA Network Analyzer. Due to not being able to measure the distance between the capacitive plate and slot ground plane, only relative distance was measured. Despite this, a rough comparison of frequency versus capacitive gap distance is seen in Figure 7. The antenna is incredibly responsive at smaller distances, rapidly changing frequency with a small change in gap. As the gap size increases, the operational frequency changes less rapidly. This is expected as the relative difference in capacitance changes as the gap size increases.

An overlay of performance at various frequencies is seen in Figure 8, showing excellent agreement between simulated and measured results. The fabricated antenna tunes from 2-4 GHz with a tuning ratio of 2:1. The maximum return loss across the entire tuning range remained above 9 dB, which is a 3 dB reduction compared to the simulated results.

The realized gain results of the fabricated slot antenna including the mount, actuator and balun are shown in Figures 9-11 for both the co-polarization and cross-polarization at 2 GHz, 3 GHz, and 4 GHz. The fabricated results closely match those of the simulated structure for the co-polarized case, with a small decrease in gain. The maximum gain is reduced from 5.09 dBi at 3 GHz ($\theta = 0^\circ$) to 4.77 dBi. An increase in cross-polarization pollution is also observed. The decrease in gain and the increase in cross-polarization can be attributed to the feeding coaxial line, the control lines, and the fixture holding the antenna in place. Overall, the radiation patterns of the fabricated slot antenna are not largely impacted by the introduction of the tuning structure as indicated by simulation results, which indicates that this type on an antenna can maintain expected
slot antenna radiation properties despite having a relatively large linear actuator and a 3D printed mounting structure in the direction of the main lobe.

The tunable slot antenna presented in this paper was deliberately designed to handle input powers much higher than antennas with other tuning methods. The input power threshold for the antenna presented in this paper should be 126 W at 3 GHz according to calculations using the breakdown voltage of the air gap between the tuning plates [23]. To verify the validity of this analysis, a high power, RF front end was used as illustrated in Figure 12. An amplifier capable of 100 W was employed, and was protected from reflection with a circulator and attenuator. This was followed by a stepped-impedance low pass filter to condition the inter-harmonic distortion of the amplifier. The signal was then passed to a bi-directional coupler for assessing the incident and reflected voltage of the antenna and then finally to the antenna itself. Using this setup, the amplifier was operated at the full 100 W with no adverse effects.

V. CONCLUSION
A tunable slot antenna allows efficient operation in a noisy spectrum. The tunable antenna introduced in this paper has been simulated to tune over all of S-band, and been demonstrated to have a tuning ratio of 2:1. It does so while
maintaining low disturbance in radiation pattern (gain > 1.73 dB), low mismatch loss (return loss > 9 dB), and efficient operation (η > 65%). The large air gaps in the tuning capacitor result in the ability to handle high power levels without non-linear effects or the threat of breakdown, as experimentally demonstrated by applying 100 W to the input of the antenna. This combination of these desirable properties is vital in applications such as phased array antennas for radars, in which maximum power, frequency agility, and noise figure are all important design limits. The antenna shown in this paper shows a promising solution to these unique challenges.

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