A Low-Loss Reconfigurable Plasma Impedance Tuner for Real-Time, Frequency-Agile, High-Power RF Applications

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***Abstract*— Many frequency bands, previously allocated solely for radar, are being designated for sharing. Future radar transmitters must adaptively share the frequency spectrum with wireless communications, requiring high-power, high-speed reconfigurable circuits to maximize radar detection range upon changes in frequency and antenna impedance. This paper presents an octave (2-4 GHz) S-band reconfigurable impedance tuner with 35 W plasma switches connecting shunt inductors and capacitors to a series feedline. The tuner can be reoptimized to maximize output power in approximately 300 µs upon changes in operating frequency or antenna impedance. The tuner has a much lower average insertion loss (2.5 dB) and comparable optimization times when compared with the previous state-of-the-art octave S-band plasma tuner. The new design significantly reduces loss over its octave tuning range using shunt inductors and capacitors instead of open-circuited stubs.**

***Keywords*—Tunable circuits and devices, impedance matching, diode lasers, semiconductor switches, cognitive radar, and electric components.**

I. Introduction

As the spectrum is becoming increasingly congested and contested, adaptive radar systems are becoming needed to handle interference from other users. The 3.45-3.55 GHz sub-band, originally allocated to radar in the United States, was recently auctioned to fifth-generation (5G) wireless providers as the primary user [1]. Much of the radar S-Band allocation has been targeted for 5G since it is a good compromise between low propagation attenuation and high available bandwidth [2]. With radar systems forced to share in this increasingly complex spectral environment, high-power radar transmitters will need to be able to utilize reconfigurable impedance tuners to maximize output power (and hence detection range) upon changes in operating frequency and antenna impedance resulting from the dynamic spectral environment. Fig. 1 shows how an impedance tuner can be placed into a power amplifier (PA) design to maximize radar transmission range. The impedance tuner replaces the fixed output matching network and can reconfigure to provide the optimum-power reflection coefficient to the PA device upon changes in operating frequency and antenna reflection coefficient Γ_{ant}.

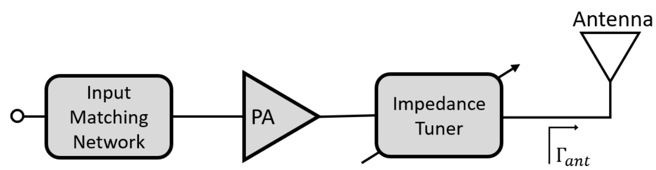

Fig. 1. Illustration of placement of impedance tuner in PA

Roessler [3] shows that using narrowband impedance tuners can provide significant increases in radar range capability over using a fixed broadband matching network due to Bode-Fano limitations on broadband design [4-5]. Several impedance tuner designs have been demonstrated to have fast reconfiguration times or high-power handling capabilities, but not both. A ferroelectric component tuner [6-7] can provide adaptation within a few microseconds but has not demonstrated above 1 W of power handling. Mechanical resonant-cavity, high-power tuners can take many seconds to reconfigure [8]. Varactor technologies have also been presented [9]. Some tuners capable of reconfiguring in tens of microseconds are limited to single-digit Watt power-handling levels [10-11]. Tuners have yet to be demonstrated that can provide both high power handling and sub-millisecond reconfiguration with low loss.

In an attempt to build an electrically actuated (fast), high-power tuner, Calabrese demonstrates a switched-stub tuner topology using radial stubs connected to a feedline with low-power field-effect transistor (FET) switches [12] and higher-power plasma switches [13], capable of tuning over the 2-4 GHz octave. The plasma switches are designed by Fisher and demonstrated to handle 35 W of RF power handling [14]. The switched-stub tuner with plasma switches can perform a complete reconfiguration optimization in hundreds of microseconds from a software-defined radio platform. However, the Calabrese tuner shows high loss, ranging from 1-34 dB, based on the use of open-circuit stubs and laser alignment uncertainties [13]. This loss quantity is daunting and limits the usefulness of the design. The present paper presents a solution to the loss issue for a plasma-tuner based design. This paper demonstrates drastically improved multi-state loss performance by using switched shunt inductors and capacitors, maintaining broad Smith Chart coverage, fast optimization capability, and high-power handling with plasma switch technology.

II. Impedance Tuner Design

Goals of the tuner design include speed, high power handling, low loss, good Smith Chart coverage, and repeatable performance. The tuner is designed to operate from 2 GHz to 4 GHz with high power handling capabilities. The Momentum Microwave Simulator in the Advanced Design System (ADS) software was used to model the electromagnetic properties of the tuner topology design and determine the optimal tuner design for our specifications. In the state-of-the-art Calabrese design [13], loss results from the use of radial open-stub lengths that present a quarter wavelength within the 2-4 GHz range, causing an RF short at the feedline and significant resulting loss. A significant tradeoff between Smith Chart coverage and loss also exists for the switched-stub tuner. As the admittance of an open-circuit stub component is increased, pushing the state outward on the Smith Chart, a trajectory is followed from the open circuit toward the short circuit on a circle of constant conductance. When placed in parallel with the antenna impedance, this causes the impedance point to emanate outward on the Smith Chart, but as high admittance (approaching a short circuit) is reached, significant current begins to flow through the branch to ground, resulting in significant loss.

Using grounded shunt inductors and capacitors attached to the feedline through the switches instead of radial stubs removes many of the high-current points on the feedline, providing much better performance. Values of inductance and capacitance were chosen such that none of the inductors or capacitors present a very large admittance to ground within the 2-4 GHz tuning range. The placement of inductors and capacitors along the feedline causes the admittances they add to depart from different regions of the Smith Chart, making different areas reachable. Fig. 2 shows a drawing of the final impedance tuner design developed in ADS using four inductors and two capacitors in a 64-state digitally controlled impedance tuner. The inductor values used were 3.3 nH and 2.5 nH, while both capacitor values were 0.4 pF.

The algorithm used for real-time reconfiguration toggles the state of each switch one at a time, using the process described in [12].

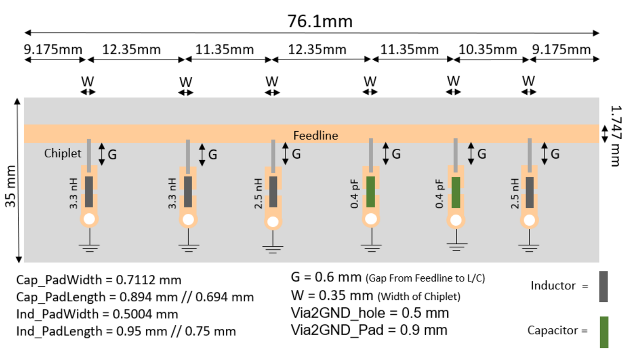

Fig. 2. Drawing of impedance tuner design using grounded inductors and capacitors

III. Impedance Tuner Fabrication

The fabricated tuner is a two-board design, consisting of an RF board with the design of Fig. 2 and a Control board that sets the tuner state and interfaces with the controlling microcontroller or software-defined radio (SDR) for execution of the reconfiguration optimization algorithm. Fig. 3 shows a cross-sectional view of the board stack-up. The RF board includes 2 oz. copper microstrip on a 31 mil FR4 board with SMA connections at the input and output of the tuner. The semiconductor plasma switches are closed by exciting the chiplets with 1 W, 940 nm laser diodes to introduce the different combinations of inductor and capacitor branches. The RF board includes non-plated through hole (NPTH) micro and blind vias with Gradient Index (GRIN) rod lenses. The lenses focus the light from the controlling diodes into the plasma switches, reducing their insertion loss values. Chiplets are fabricated using the design presented by Fisher [14]. The chiplets are 350 μm wide with total length of 1.675 mm, bridging the 600 μm gap between the microstrip line and each reactive element.

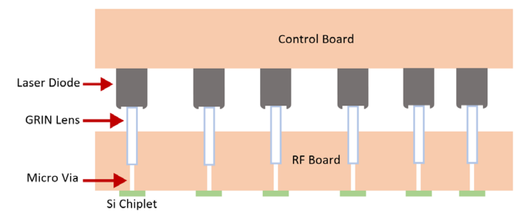

Fig. 3. Cross-sectional illustration of tuner alignment stack-up

Care was given to alignment of the boards in fabrication to obtain repeatable and reliable results. Initial designs used two plastic screws and nuts to hold the boards into place. However, since the alignment precision is on the order of μm, it was very easy for the boards to fall in and out of alignment when adjusting the screws. A new alignment method was developed utilizing precise custom machined aluminum brackets adhered to each board and steel screws to firmly hold the boards in the optimal alignment between the laser diodes and the silicon chiplets.

IV. Measurement Results

The measurement test setup consisted of an SDR/microcontroller (to control the search algorithm and set the tuner state), SkyWorks SKY65017-70LF amplifier, the plasma tuner, and a Maury Microwave commercial impedance tuner (used to represent the changing presented antenna reflection coefficient Γ_{ant}). A network analyzer was used to measure S-parameters of the tuner, allowing calculation of the loss and Smith Chart coverage. Fig. 4 shows the measured Smith Chart coverage of the tuner. A useful coverage, very comparable to that reported by Calabrese [13] is achieved over the entire octave tuning range.

Fig. 5 shows the loss of the 64 tuning states over the 2-4 GHz octave tuning range, calculated as follows:

$$Loss = -10 * \log_{10}\left(\frac{|S_{21}|^2}{1-|S_{11}|^2}\right) \quad (1)$$

The loss shown in Fig. 5 is much lower than the previously reported results from the Calabrese switched-stub topology [13]. The average loss for all states and measured frequencies is approximately 2.5 dB, with a maximum loss of 5.7 dB, compared to the Calabrese tuner [13], possessing an average loss of 7.7 dB and a maximum loss of 34.2 dB. This means that many more states without disqualifying loss values are available for impedance matching in our design. The 90%-10% on and off times were measured as 3.6 μs and 26.7 μs, respectively, very similar to the times given for the plasma-switch tuner in [13].

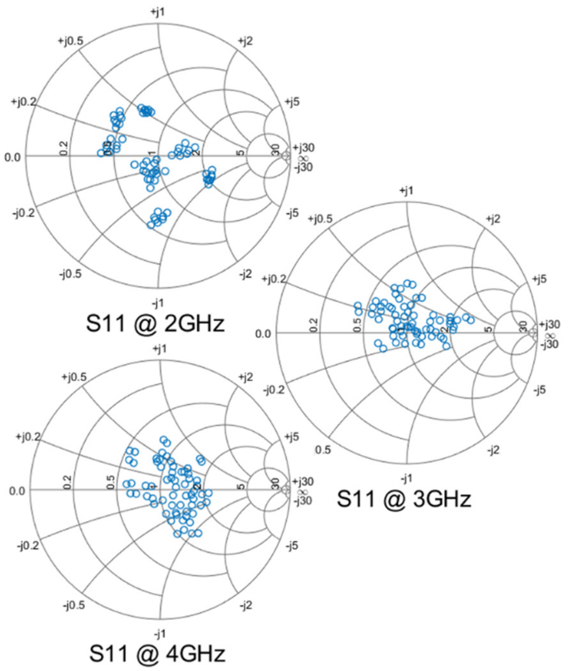

Fig. 4. Measured Smith Chart coverage of all 64 states at 2 GHz, 3 GHz, and 4 GHz

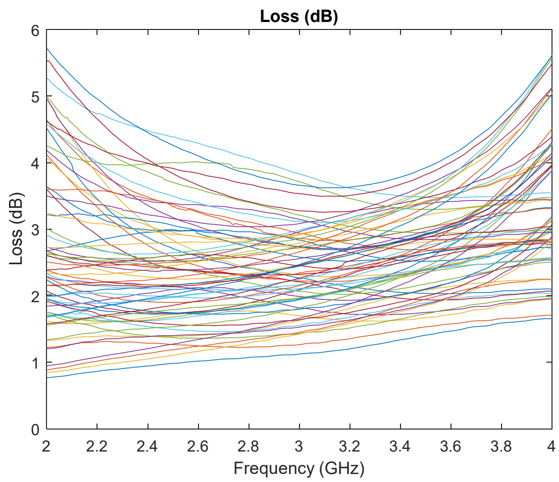

Fig. 5. Measured loss of all 64 tuner states from 2-4 GHz

Timed measurement executions of the optimization algorithm used by Calabrese with the switched-stub tuner [12, 13] were performed using a SDR controller, and are shown in Table 1. In this search algorithm, the six switches are all toggled on in order from input to output, one at a time. If better output power is achieved, the switch is left on, whereas if worse output power is achieved, the switch is returned off. The process continues until a complete cycle of all switches is performed with no change in switch position. The Skyworks amplifier, with 3 dBm input power, was used as the active device. The Maury Microwave tuner was used to emulate the changing antenna reflection coefficient Γ_{ant}. The search was performed at different combinations of operating frequency and Γ_{ant}. Table 1 shows that searches were completed in an average of about 300 μs, with an individual search step requiring less than 27 μs, very comparable to the results reported by Calabrese for the switched-stub tuner [13]. However, with the greater number of low-loss options in this tuner, many different binary states of switch combinations (1 = on, 0 = off from input to output) were selected by the algorithm for optimum matching. This tuner provides excellent versatility in achieving an acceptable match without sacrificing large loss amounts.

VI. Conclusions

An impedance tuner with switched shunt capacitors and inductors using 35 W semiconductor plasma switches has been presented. A significant performance improvement is observed in multi-state loss compared to the previous state-of-the-art switched-stub tuner design. An average insertion loss of only 2.5 dB over all measured frequencies and states was obtained, with complete optimization-based reconfiguration on an average of 300 μs from a software-defined radio platform. The measured tuner is fast, capable of high power handling, and possesses much improved multi-state loss versus the state of the art, and can be used for adaptive radar and other high-power S-band transmitter applications.

Table 1. Tuner optimization results

Freq. (GHz)	Γ_{ant}	# Meas.	Time (μs)	Max. Power (dBm)	Best State [Bin (Dec)]
2.0	0.50/45°	10	297.79	14.32	010100 (20)
2.0	0.30/120°	10	297.79	14.34	011100 (28)
2.5	0.00/0°	9	268.01	14.03	011000 (24)
2.5	0.30/120°	17	506.25	14.14	000011 (3)
3.0	0.00/0°	12	357.35	12.20	000001 (1)
3.0	0.50/45°	10	297.79	10.21	000100 (4)
3.5	0.30/120°	12	357.35	8.53	000101 (5)
3.5	0.40/310°	12	357.35	8.49	010001 (17)
4.0	0.00/0°	7	208.46	11.08	000000 (0)
4.0	0.32/10°	12	357.35	10.52	001001 (9)

Acknowledgment

This work relates to Department of Navy award (Award No. N00014-19-1-2549) issued by the Office of Naval Research. The United States Government has a royalty-free license throughout the world in all copyrightable material contained herein.

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