Enhancing Frequency-Agile Radar Range over a Broad Operating Bandwidth with Reconfigurable Transmitter Amplifier Matching Networks

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***Abstract* – Tunable narrowband impedance matching networks (MNs) can be used to optimize output power in real time, maximizing radar range after operating-frequency changes in spectrum sharing radar transmitters have been accomplished. This paper compares the performance of two similar power-amplifier (PA) designs: one with a fixed, broadband output MN and the other with a tunable, narrowband output MN. The 50 Ohm stable PAs were designed for optimal gain performance in the operating range of 3.1 GHz to 3.5 GHz, with the harmonics terminated to maximize gain. Simulation results show that the design with the tunable output MN can achieve greater than 2 dB increase in gain across the entire frequency range over a fixed broadband MN design. This allows a significant increase in output power and radar detection range, with reconfiguration time being the primary tradeoff incurred from using a reconfigurable matching circuit.**

***Keywords* – Broadband amplifiers, tunable circuits and devices, impedance matching, cognitive radar**

I. Introduction

Spectrum-sharing radar systems must maintain significant range coverage over a wide band of frequencies. The recent release of significant S-band radar spectrum in the United States for sharing with wireless communications requires that radar systems be capable of switching operating frequency quickly. At the same time, the transmitter circuits must maintain detection range upon such required changes in operating frequency. Of particular importance is the transmitter PA, which must provide the necessary output power and is the major driver of the system power efficiency. Two options exist for a PA that can quickly change its operating frequency: a fixed-circuit, broadband amplifier or a reconfigurable-circuit narrowband amplifier.

In 1948, Fano explained the limitations on broadband matching of arbitrary impedances [1]. Along with Bode [2], he derived the well-known Bode-Fano Criterion, which shows that the gain-bandwidth product of a passive circuit is constant. In designing circuits for systems required to share spectrum, amplifiers with broadband matching are a viable option. However, the Bode-Fano Criterion dictates that the quality of the match, and hence the gain of the amplifier, will be compromised when trying to obtain wide operating bandwidth. Thus, a narrowband, tunable MN would suggest an optimal alternative that can maximize gain, output power, and range when changing operating frequency to share spectrum [3].

There have been numerous established methods of achieving a fixed amplifier design to provide the highest feasible gain when using a broadband design [4 - 6] however; it is suspected, based on the Bode-Fano Criterion, that these designs will not manifest the higher gain values of a narrowband design. Given the Bode-Fano restriction, either gain or bandwidth can be selected as the most important parameter in an amplifier with fixed circuitry, or a compromise between gain and bandwidth can be sought. On the other hand, a tunable matching network can be designed to obtain the maximum possible gain over a narrow band of frequencies, with the capability of shifting the gain maximum throughout the frequency band of operation as the system changes its operating frequency. Tunable MNs are critical to maximizing radar range while allowing real-time spectrum sharing in cognitive and adaptive radar systems. However, fast, real-time tuning of this reconfigurable circuit is needed to allow fast changes in operating frequency [3].

A simulation experiment to demonstrate the tradeoff between fixed PAs with broadband MNs and reconfigurable PAs with tunable, narrowband MNs is detailed in the following sections where possible benefits and drawbacks of each approach are explored. The simulation results demonstrate that, consistent with the Bode-Fano Criterion, higher gain can be achieved by a narrowband tunable MN. However, time is required to reconfigure the network following a change in operating frequency, whereas a broadband MN does not require reconfiguration thus eliminating the time penalty.

II. Simulation Setup and Procedure

An Infineon BFP420 bipolar junction transistor (BJT) [7] was selected as the transistor for this simulation comparison, and a Modelithics nonlinear model for the device was used in

Keysight Technologies' Advanced Design System (ADS) for the simulations. The tunable MN used is a model for the Semnani evanescent-mode cavity impedance tuner [8], designed to perform impedance tuning between 3.1 and 3.5 GHz (a significant part of the United States radar S-band allocation). An equivalent circuit diagram is presented in [8].

Using a traditional amplifier design approach detailed by Gonzalez [9], a baseline design approach was similarly applied to both amplifiers, seeking conjugate input matching, 50 Ω stability, and maximizing gain and bandwidth in all scenarios. However, one amplifier was designed for fixed, broadband performance; while the other system was designed for tunable, narrowband performance. The fixed amplifier uses a T-shaped, three-element broadband output matching network (OMN), along with an input matching network (IMN) designed to provide a conjugate match to the input reflection coefficient of the transistor ($\Gamma_s = \Gamma_{\mathrm{IN}}^*$). To simulate a narrowband, tunable MN, the Semnani tuner model was implemented in place of the OMN from the fixed network.

For the reconfigurable PA, the IMN was redesigned to provide the conjugate match to the input of the transistor ($\Gamma_s = \Gamma_{\mathrm{IN}}^*$) at 3.3 GHz with the tuner configured to provide an output power match at 3.3 GHz. The IMNs of both amplifiers were designed as L-shaped, two-element MNs. The performance of the amplifier with the tunable OMN was compared to the performance of the amplifier with the fixed broadband MN. Fig. 1 shows a block diagram comparison depicting the differences between the two designs and how each PA was constructed. Since the only significant difference between the designs is the OMN type, the advantages and disadvantages of both OMN types can be compared and analyzed.

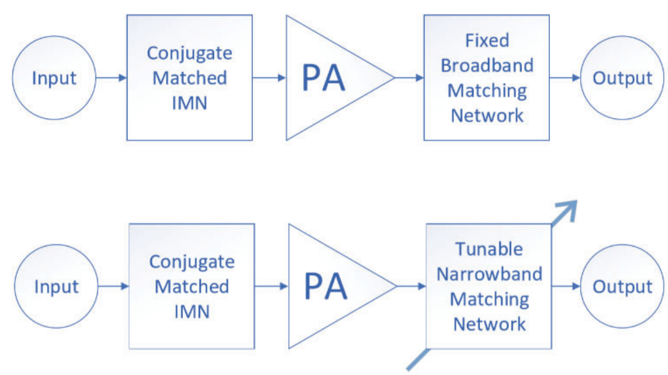

Fig. 1. Block diagram comparison between the amplifier designs with the fixed, broadband MN amplifier and the tunable, narrowband MN.

Figs. 2 and 3 show the circuit schematics for the fixed and reconfigurable amplifiers, respectively. First, a bias point was selected for the BJT transistor to operate in a stable environment with high gain. A three-resistor bias network was designed to provide the desired transistor voltage and current values. The grounding of the emitter in the three-resistor design minimizes unwanted potential negative feedback, yielding higher gain and output power. Additionally, increasing the values of R1 and R2 in the circuits of minimizes the current that is used to bias the transistor properly, which improves the efficiency and minimizes power consumption from the DC power supply. DC blocking capacitors (C2 and C3) and RF chokes (L2 and L4) are implemented into the design to isolate the DC and the RF signals from each other.

After ensuring proper biasing, the IMN was designed to provide a complex conjugate match to the input of the transistor. A low pass L-shaped MN was used to provide this match since it was shown to yield the highest gain when compared to other topologies. After the IMN design, the fixed, broadband OMN was designed to provide a gain match at the output of the transistor. For this OMN, a T-shaped MN was implemented to reach a low quality (Q) factor on the Smith Chart before providing a match to the output of the transistor. The low Q condition was sought to ensure a broadband match from 3.1 GHz to 3.5 GHz.

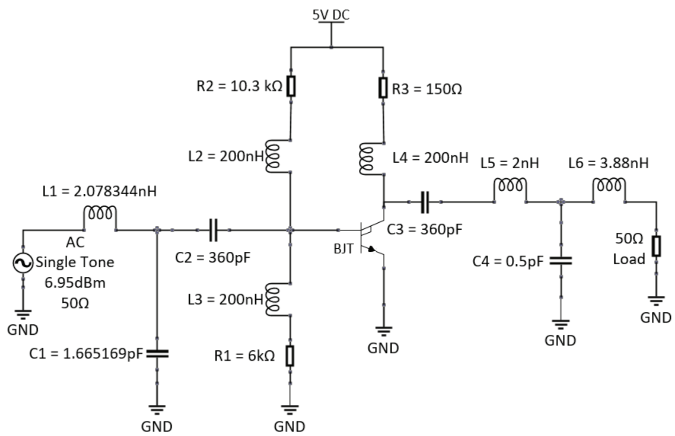

Fig. 2. Fixed broadband amplifier design.

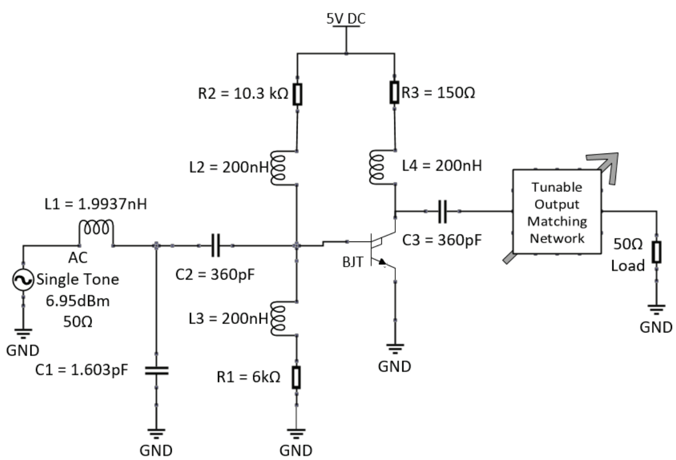

Fig. 3. Tunable narrowband amplifier design.

In order to provide a complex conjugate impedance match at the input while maintaining the desired output power match and performance bandwidth, an iterative process was used. By repeatedly tuning to maximize gain in the OMN and then redesigning the IMN to provide a conjugate match to the new transistor input reflection coefficient, the process eventually converged to an equilibrium point. The simultaneous conjugate match at the input and a gain match at the output provided the fixed network with the highest possible gain over the entire frequency range for the design.

With the fundamental impedance optimized, the harmonic terminations must also be considered. In a nonlinear PA, harmonic terminations can play a significant role in the gain of the amplifier. Collinson demonstrates that the efficiency of the amplifier can vary up to 40% based on the choice of harmonic terminations [10]. As such, the harmonic terminations were optimized for each network to minimize their effect on the amplifier comparison. The second, third, fourth, and fifth harmonic terminations were chosen to avoid any power in the harmonics being lost due to unoptimized reflections. The harmonics were terminated by using another iterative design process with the fundamental-frequency MNs to achieve the optimal gain in both PA designs. The process of terminating the harmonics used an array based set of idealized terminations that shifted with each harmonic. The harmonics were reflected back to the output of the transistor with an optimized phase that would add constructively to the fundamental, while maintaining a conjugate match at the input, as well as an optimal gain match at the output. The fundamental frequencies were terminated with an ideal through, thus the terminations had no effect on the fundamental frequencies. The harmonics were terminated optimally at only the center frequency (3.3 GHz); to yield the highest gain possible. After the iterative process converged to an optimum, the harmonic terminations were fixed in the design.

For the tunable amplifier, the harmonics were fixed to provide optimal performance at the center frequency of the selected frequency band (also 3.3 GHz in the initial case). This coincidence permits a direct comparison of the results obtained between the tunable, narrowband MN and the fixed, broadband MN. For the fixed amplifier, the harmonics were terminated to fine-tune the amount of gain variation allowed across the entire operating frequency range, of the fixed broadband network. To allow more gain variation, the phase of the harmonic reflections at the load may be adjusted.

Fig. 3 shows the schematic of the tunable, narrowband network. The same iterative design process was conducted for the tunable network. However, instead of altering the component values in the OMN, the cavity heights of the Semnani tuner were changed to present the optimal load impedance to provide the highest gain. Eventually, the process converged to a narrowband optimum at the center frequency of the design (3.3 GHz). The source match and ideal harmonic terminations are fixed to optimize performance at the center of the band (3.3 GHz), and only the fundamental load impedance is reconfigured as operating frequency varies. While the device does impose a time penalty to reconfigure "on the fly" upon changes in operating frequency, the reward is increased radar detection range can be achieved over the entire narrowband frequency range of operation.

III. Simulation Results

Once the designs were completed, both the input conjugate match and 50 Ω stability of the designs were verified. With the harmonics terminated optimally at 3.3 GHz for each network, the schematics were simulated to show the performance of each design. The tunable network was tuned to optimize the gain at three different frequencies in the range of operation (3.1 GHz, 3.3 GHz, and 3.5 GHz). Fig. 4 shows these obtainable gain values at their respective frequencies. After reconfiguring the narrowband MN, a gain of 9.911 dB is attainable at 3.1 GHz, a gain of 10.052 dB is attainable at 3.3 GHz, and a gain of 9.425 dB is attainable at 3.5 GHz.

For comparison, Fig. 5 shows the gain for broadband designs designed with three different allowable gain variations over the 3.1-3.5 GHz band of interest: 0.1 dB, 0.5 dB, and 1 dB. For the design allowing 0.1 dB of in-band variation, a gain between 7.277 dB and 7.339 dB was achieved over the 3.1 to 3.5 GHz band. For the design allowing 0.5 dB of in-band variation, a gain variation from 7.695 dB to 8.185 dB is achieved. For a design performed with a goal of 1 dB maximum in-band variation, a gain variation from 7.353 dB to 8.359 dB was obtained. The narrowband tunable network, at its worst-performing tuned frequency in the band, is still able to achieve more than 1 dB gain improvement over the best result obtainable from the broadband MN.

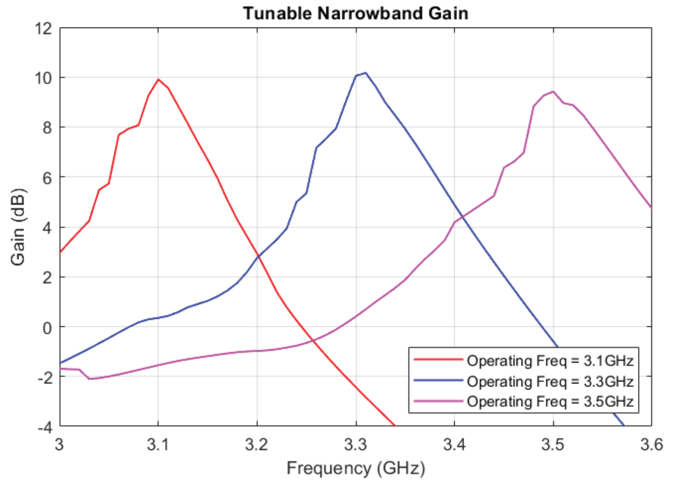

Fig. 4. Tunable narrowband gain attainable by reconfiguring the load MN for gain performance at 3.1 GHz (red), 3.3 GHz (blue), and 3.5 GHz (pink).

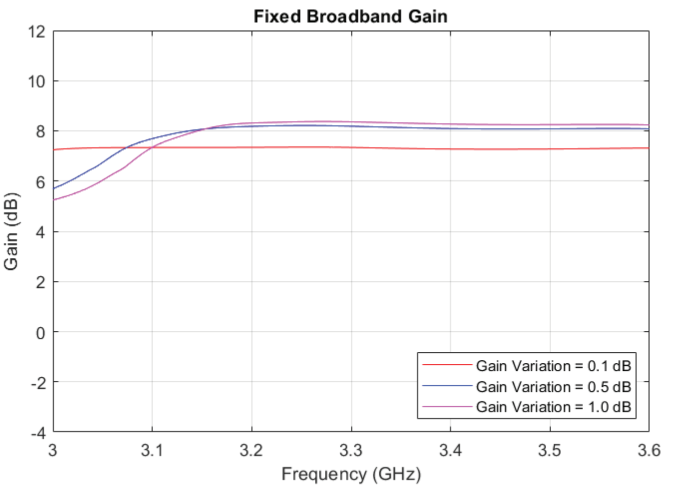

Fig. 5. Fixed broadband MN gain versus frequency for designs allowing 0.1 dB variation (red), 0.5 dB variation (blue), and 1.0 dB variation (pink) in the 3.1-3.5 GHz band

Depending on the application, the variation in gain could be critical. With a very flat, fixed broadband MN design, there is approximately the same radar range over the entire frequency band. However, as increasingly more gain variation is allowed, the radar range at certain operating frequencies can be increased with performance degradations at other points in the PA's frequency band. Furthermore, by continuing to increase the variation in gain, the fixed OMN approaches the narrowband tunable design, corresponding with expectations from the Bode-Fano Criteria.

Table I summarizes the performance of the tunable MN and the fixed broadband MNs. Equation (1) was used to determine the percent improvement in radar range. This relationship is obtained from the traditional radar range equation (2) by assuming each radar has the same operating conditions with the exception of the different OMN and by expressing the result in percent improvement. With 50 Ω stable conjugate matched networks and optimally terminated harmonics, the tunable network was able to obtain a 2-3 dB increase in gain over the 0.1 dB gain variation fixed OMN version for the entire frequency band. For radar design, this improvement in gain will yield a larger output power that will increase the detection range of the radar. For an input power of 6.95 dBm, these gain values correspond to a radar detection range improvement of 13.2% to 16.9% over the operating frequency range. Table I provides a comparison between the networks' gain values across the operating frequency range, as well as the percent increase in radar range available with a tunable MN as compared to a fixed broadband MN for typical radar parameters. With a tunable network, the radar will maintain the ability to shift operating frequencies while maintaining optimal gain and detection range.

TABLE I: PERCENT IMPROVEMENT IN RADAR RANGE COMPARISON OF EACH PA NETWORK (PERMITTED GAIN VARIATIONS UNDERLINED)

Frequency (GHz)	Fixed Broadband Gain (dB)			Tunable Narrowband Gain (dB)	Percent Improvement in Radar Range(%)		
	0.1dB	0.5dB	1 dB		0.1dB	0.5dB	1 dB
3.1 GHz	7.336	7.695	7.353	9.911	15.98	13.61	15.86
3.3 GHz	7.339	8.185	8.359	10.052	16.9	11.35	10.24
3.5 GHz	7.277	8.079	8.248	9.425	13.16	8.056	7.01

$$\%_{Improvement} = \left(\sqrt[4]{\frac{Gain_{Tunable}}{Gain_{Fixed}}} - 1\right) * 100\% \quad (1)$$

$$Range = \sqrt[4]{\frac{P_{out} * G_{Antenna}^2 * \left(\frac{c}{f}\right)^2 * \sigma * Pulse\_Duration}{(4\pi)^3 * Loss * T * k * SNR}} \quad (2)$$

One cost of this ability to maximize gain through impedance tuning is the reconfiguration time. The tuner of Semnani is able to transition from one tuner state to another in between 30 ms to 300 ms. For a complete search with no initial information, as long as 5 to 10 seconds can be required, but initializing the search based on previous search results stored in a look-up table can speed a tuning search to 1.5 second [11]. Additional methods have been devised for adjusting the tuning algorithm to target average performance [12], allowing it to successfully improve system performance when the operating frequency is transitioned much faster than the tuner search time. Alternative high-power, electrically actuated tuners would likely be capable of reconfiguration in under 1 ms. Such an approach would reduce the cost of reconfiguration time and improve the feasibility of optimization.

V. CONCLUSIONS

A simulation study performed in the 3 GHz radar band shows that reconfigurable MNs may be used in radar transmitter PAs to increase range in spectrum sharing, frequency-agile scenarios. Gain performance was analyzed for two similar amplifier designs, one possessing a fixed broadband OMN to cover the 3.1 GHz - 3.5 GHz band and the other possessing a reconfigurable MN designed to be tuned over the 3.1 GHz - 3.5 GHz band. Significant improvements in gain and radar range were observed for the design using the reconfigurable OMN, compared to the fixed broadband MN. The simulation results are consistent with the theoretical Bode-Fano Criterion, which states that the gain-bandwidth product of a MN is constant. The maximum gain of the tunable, narrowband design was approximately 1 dB to 2.5 dB higher than the gain of the fixed, broadband design. These results show that reconfigurability in a radar transmitter MN for spectrum sharing can result in up to a 16.9% improvement in radar detection range by using a tunable MN. This reconfigurability comes at a penalty of tuning time required to re-tune the MN upon changing operating frequencies. Some other penalties that come with implementing a reconfigurable OMN are complexity, cost, and loss. However, research for improving the reconfiguration times, as well as the other penalties listed, is ongoing. An early version of a high-power plasma-switch impedance tuner has been completed and is illustrated by Calabrese in [13].

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