GaAs MMIC Tunable Directional Coupler

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***Abstract*—This paper presents a tunable GaAs MMIC directional coupler. Design equations for a hybrid coupler with ideal tunable capacitances are derived to determine the range of capacitances for the desired coupling tuning range. The 2 GHz coupler is implemented in a 0.5 μm GaAs process with Schottky varactor diodes, and occupies an area of 2.2 mm × 1.4 mm. Over a bias range of 0 V to -1.5 V the coupling coefficient ranges from 6.6 to 60 dB, or 53.4 dB of dynamic range at 2 GHz. The input return loss for the device is better than 12 dB for all bias voltages and is better than 20 dB for coupling coefficients from 23 to 60 dB with isolation better than 17 dB.**

***Index Terms*—Directional couplers, tuning, MMICs.**

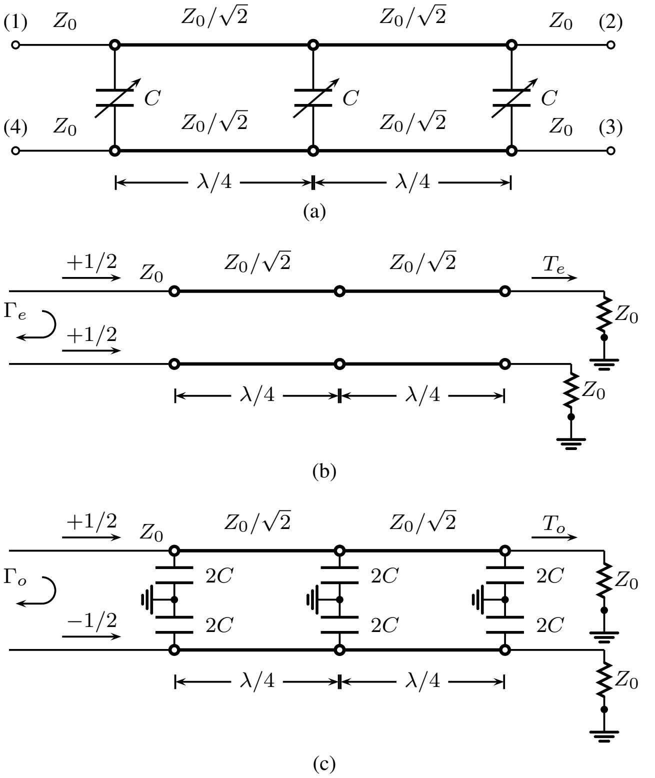

Fig. 1. Tunable directional coupler topology (a) with the even (b) and odd (c) mode equivalent circuits where Γ_e and T_e corresponds to the even mode reflection and transmission coefficients and Γ_o and T_o corresponds to the odd mode reflection and transmission coefficients.

I. INTRODUCTION

Recently there has been increased interest in wearable on-chip radiometers [1] for applications such as diagnosing elevated temperatures in infant brains [2], breast cancer detection [3], and monitoring of arthritis [4]. A balanced Dicke radiometer [5], is an appropriate architecture for these applications, and a conventional approach uses a variable attenuator and fixed directional coupler. Alternatively, a MMIC variable coupler can replace these two components, thus making the wearable radiometer more compact. Additional applications include tunable impedance transformers [6].

Couplers with tunable coupling ratios have been presented in [6]–[10], with a thorough comparison of variable directional couplers presented in [10]. In this paper, the simplified coupler model analysis is first presented, followed by results on a GaAs MMIC.

II. TUNABLE COUPLER ANALYSIS

Considering a simplified directional coupler circuit with ideal variable capacitors as shown in Fig. 1a. The even and odd mode circuits are shown in Figs. 1b and 1c respectively. The even mode transmission and reflection coefficients are

$$\Gamma_e = 0 \quad , \quad T_e = -1 \tag{1}$$

and the odd mode transmission and reflection coefficients are given by

$$\Gamma_o = \frac{-B^3 Z_0^3}{B^3 Z_0^3 - j2B^2 Z_0^2 - 2BZ_0 + j} \tag{2}$$

$$T_o = \frac{-j}{B^3 Z_0^3 - j2B^2 Z_0^2 - 2BZ_0 + j} \tag{3}$$

where $B = 4\pi f C$. The four port scattering parameters are now found from the even and odd mode transmission and reflection coefficients. Solving for the match and isolation conditions ($S_{11} = S_{41} = 0$) yields a solution of $\Gamma_o = 0$, implying $B = 0$ and $T_o = -1$, however, this trivial solution does not allow for tuning the coupling given by

$$S_{31} = \frac{1}{2} T_e - \frac{1}{2} T_o = -\frac{1}{2} \left(1 + T_o\right). \tag{4}$$

The approximate solution is found by expanding Γ_o in a Taylor series about $B = 0$ to second order, which still satisfies the matched and isolated condition

$$S_{11} = -S_{41} = \frac{1}{2} \left(\Gamma_o(0) + B\Gamma_o'(0) + \frac{B^2}{2} \Gamma_o''(0) \right) = 0. \tag{5}$$

Repeating for the coupled port results in

$$\begin{aligned} S_{31} &= -\frac{1}{2} \left(1 + T_o(0) + BT_o'(0) + \frac{B^2}{2} T_o''(0) \right) \\ &= -jBZ_0 - B^2 Z_0^2 \end{aligned} \tag{6}$$

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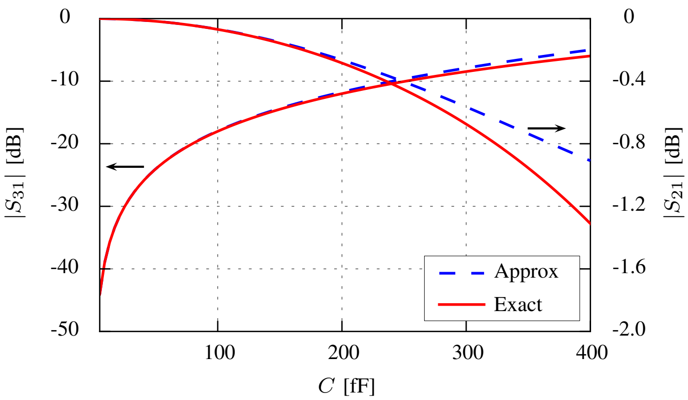


Fig. 2. Comparison of $|S_{21}|$ and $|S_{31}|$ vs. tuning capacitance C at 2 GHz for both the exact solution (solid line) and the solution based on the Taylor series approximation (dashed line).

which is still dependent on B. Similarly, the expression for the through port is given by

$$\begin{aligned} S_{21} &= \frac{1}{2}\left(-1 + T_o(0) + BT_o'(0) + \frac{B^2}{2}T_o''(0)\right) \\ &= -1 + jBZ_0 + B^2Z_0^2. \end{aligned} \quad (7)$$

The phase difference from the coupled port to the through port is given by the following approximation

$$\arg(S_{21}) = \tan^{-1}\left(\frac{BZ_0}{B^2Z_0^2 - 1}\right) \approx \tan^{-1}(-BZ_0) \quad (8)$$

$$\begin{aligned} \arg(S_{31}) - \arg(S_{21}) &= \tan^{-1}\left(\frac{1}{BZ_0}\right) - \tan^{-1}(-BZ_0) \\ &= \frac{\pi}{2}. \end{aligned} \quad (9)$$

Eq. (5) demonstrates the coupler is matched and isolated while the coupled and through ports are dependent on B and thus can be varied if B can be varied. Additionally, the phase difference between the coupled and through ports is 90°. These conditions are valid for B close to zero. Solving (6) for B and using $C = B/4\pi f$ gives two solutions for C as a function of the magnitude of coupling, the positive solution is chosen for a capacitance

$$C = \frac{\sqrt{2\left(\sqrt{4|S_{31}|^2 + 1} - 1\right)}}{8\pi f Z_0}. \quad (10)$$

Using (10) for a desired tuning range of $|S_{31}|$ between -40 and -5 dB corresponds to $C = 8$ fF to $C = 400$ fF, respectively. The accuracy of making an approximation based on a Taylor series expansion to second order is shown in Fig. 2. The approximation is within 0.01 dB for small values of C and is within 1 dB of the exact value for $|S_{31}|$. The ideal tunable coupler was analyzed over a frequency range of 1.5 to 2.5 GHz for $C = 8$ fF and $C = 400$ fF. Fig. 3 demonstrates a coupling coefficient from - 8 dB to - 41 dB for a capacitance from 400 fF to 8 fF, while maintaining a return loss greater than 27 dB at 2 GHz.

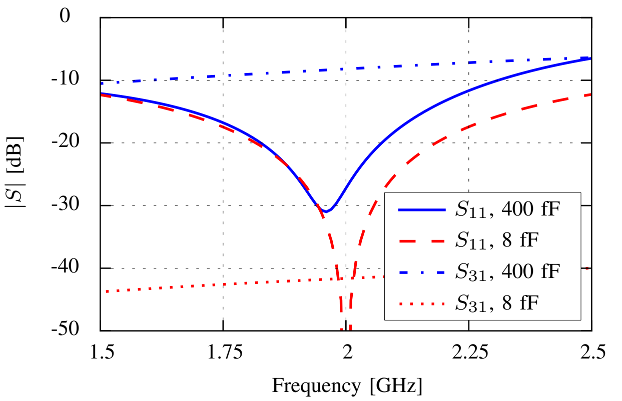
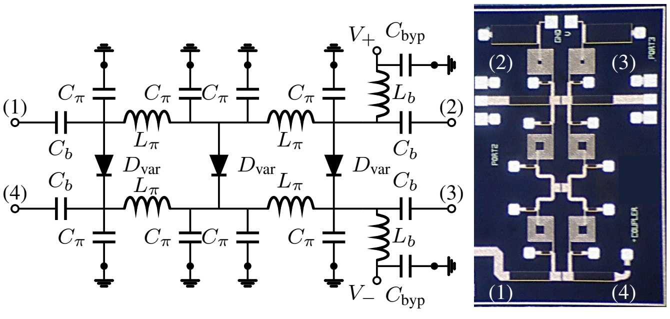


Fig. 3. Simulated results for S_{11} and S_{31} for the tunable coupler demonstrating a tuning range of 34 dB on S_{31} while maintaining a return loss of greater than 27 dB at 2 GHz.



(a) (b)

Fig. 4. Tunable directional coupler topology (a) and a photograph (b) of the GaAs MMIC coupler. The chip occupies an area of 2.2 mm × 1.4 mm neglecting probe pads and test structures.

III. MMIC Coupler Implementation and Results

The proposed MMIC tunable directional coupler schematic is shown in Fig. 4a. Due to size constraints the $\lambda/4$ transmission lines are implemented using π-equivalent networks with C_π and L_π to synthesize a 70.71 Ω $\lambda/4$ line at 2 GHz. The variable capacitance is obtained by applying a varying bias to three depletion mode Schottky diodes (D_{var}). To reduce circuit size, on-chip bias tees were realized using an inductor and a shunt capacitor. The bias network is simplified by applying the same bias to each of the three Schottky diodes so only two DC bias lines are needed. There are four DC blocking capacitors on each port to block the DC bias from the output. This simplified bias network aids in reducing the overall size and complexity of the circuit. The tunable directional coupler was fabricated in a 0.5 μm GaAs commercial (TQS TQPED pHEMT) process. A photograph of the coupler is shown in Fig. 4b. The chip occupies an area of 2.2 mm × 1.4 mm neglecting probe pads and test structures. The $\lambda/4$ 70.71 Ω lines were realized with two shunt metal-insulator-metal (MIM) capacitors (C_π) connected with a spiral inductor (L_π). The MMIC tunable directional coupler was characterized by doing three separate measurements on a two-

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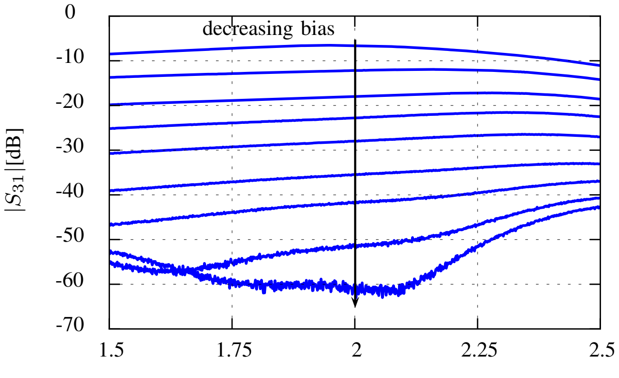

Fig. 5. Measured S-Parameters for the coupled port demonstrating a tuning range of -6.6 dB to -60 dB at 2 GHz for $|S_{31}|$. The depletion mode diode was reverse biased so the coupling varies by decreasing the bias voltage from 0 V to -1.2 V.

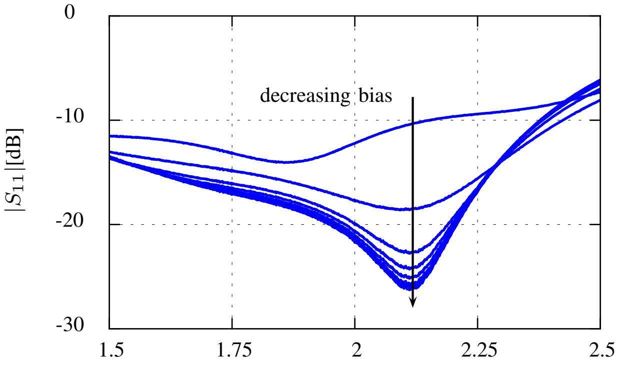

Fig. 6. Measured input return loss for the tunable coupler demonstrating better than 12 dB return loss for all bias conditions at 2 GHz. The return loss improves to better than 20 dB over a wide coupling coefficient tuning range from 18 dB to 41 dB.

port network analyzer. The die was probed using 150 μm pitch probes with an SOLT calibration using an impedance standard substrate (ISS). The four port tunable coupler was characterized with an assumption of symmetry. The fourth or isolated port was terminated on-chip with a 50 Ω resistor, the coupler was then characterized by taking three separate two port measurements with the third port terminated with a load connected to an RF probe. The insertion loss ($|S_{21}|$), coupling coefficient ($|S_{31}|$), and isolation ($|S_{41}|$) were measured shown in Figs. 5 to 7 with the following conclusions:

- the coupling coefficient varies from 6.6 dB to 60 dB, corresponding to a dynamic range of 53.4 dB
- the input match of the coupler is better than 12 dB for all bias points, improving to better than 20 dB for large coupling coefficients
- the isolation ranges from 17 dB to 40 dB as the bias decreases

Simulated and measured data for relevant coupling coefficients up to 28 dB are compared in Table I showing the simple architecture from Figs. 1a and 4a can be used effectively for designing integrated variable couplers.

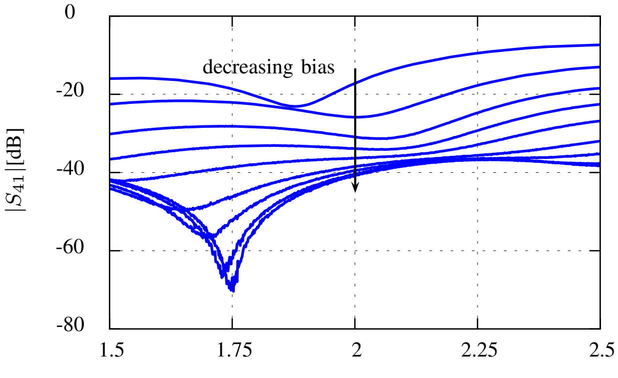

Fig. 7. Measured isolation greater than 17 dB for all bias conditions. The isolation of the coupler improves to 40 dB with decreasing bias.

TABLE I
COMPARISON OF SIMULATED AND MEASURED RESULTS AT 2 GHZ.

	Bias [V]	$\|S_{11}\|$ [dB]	$\|S_{21}\|$ [dB]	$\|S_{31}\|$ [dB]	$\|S_{41}\|$ [dB]
Meas.	0	-12.2	-7.1	-6.6	-17.2
Sim.	0	-11.1	-7.4	-5.2	-14
Meas.	-0.8	-21.2	-2	-28	-36.3
Sim.	-0.8	-23.9	-1.3	-26.3	-45.9

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