A Full-duplex Bidirectional Amplifier with Low DC Power Consumption Using Tunnel Diodes

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***Abstract*—A low-power, switchless, full-duplex bidirectional amplifier operating in the 915 MHz (ISM band) is proposed. It is composed of two identical reflection amplifiers and one $90^{\circ}, -3$ dB Branch Line Coupler (BLC). The reflection amplifiers are designed using low DC power consumption tunnel diodes and provide a measured reflection gain of 13 dB with consumed power of only 178 μW for -30 dBm of incident signal power. These reflection amplifiers are integrated with a miniaturized BLC to form a bidirectional amplifier that provides 9 dB of measured transmission gain and 22 dB of measured return loss.**

***Index Terms*—Bidirectional amplifier, negative resistance, reflection amplifier, smart RFID, retro-directive antenna arrays.**

I. Introduction

BIDIRECTIONAL amplifiers have found many applications in wireless systems including half-duplex and full-duplex radio transceivers [1]–[3], retro-directive antenna arrays [4], [5], and read/write smart RFID tags [6].

There are two types of bidirectional amplifiers: half-duplex and full-duplex [7]. Half-duplex bidirectional amplifiers amplify the input signal in one direction each time. They can be implemented using a unilateral amplifier in each direction and selecting the path by RF switches [8] or transistor network configuration [1], [2], [4], [9]. Full-duplex bidirectional amplifiers, on the contrary, amplify the incoming signal in both directions simultaneously. They can be realized by using two identical one-port reflection amplifiers and a BLC [5], using two identical unilateral amplifiers and two RF circulators [7] or by implementing a network of amplifiers in MMIC technology [10]. Transistor based amplifiers DC power consumption reaches up to 330 mW [11] and complex design is needed. Using RF circulators to separate the signal paths also makes the circuit bulky.

In this paper, we present a low power consumption and simple design bidirectional amplifier adequate for RFID applications. It has been designed using two low power tunnel diodes as the reflection amplifiers, which have been integrated by a BLC to form the bidirectional amplifier. The proposed bidirectional amplifier structure has been analyzed theoretically, simulated and fabricated. We achieved 9 dB transmission gain between the input/output ports with 22 dB return loss at the ports. The total power consumption is 356 μW which can be easily provided by ambient energy harvesting method, coin battery or a charge pump in fully passive circuits [12]. Table I is a comparison between this work and similar bidirectional amplifiers.

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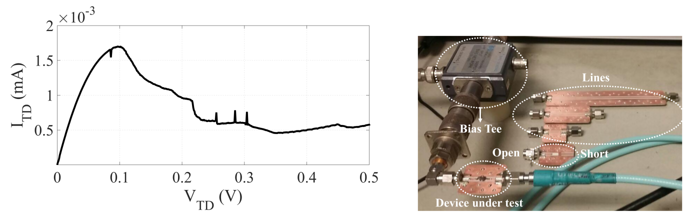

(a) (b)

Fig. 1: (a) The I-V curve of AI201A tunnel diode and (b) the TRL calibration set for the tunnel diode S-parameters extraction.

Work	Technique used	Power consumption	Gain	Size	Frequency
[5]	Two transistor-based reflection amplifiers + one BLC	___	8.1 dB	___	6.2 GHz
[7]	Two identical unilateral amplifiers + two RF circulators	750 mW	8 dB	λ/2.5 ×λ/3.5	2.4 GHz
[10]	Network of amplifiers in MMIC technology	750 mW	27 dB	λ/12 × λ/16	10 GHz
This paper	Two tunnel diode-based reflection amplifiers + one BLC	356 µW	9 dB	(λ/4.3) × λ/7	0.9 GHz

TABLE I: Comparison of the proposed bidirectional amplifier with some similar full-duplex bidirectional amplifier.

II. Reflection amplifier

The proposed bidirectional amplifier consists of two identical reflection amplifiers and a microstrip BLC. The key ingredient to achieve a *low-power* bidirectional amplifier is to design a low-power reflection amplifier. Since a tunnel diode can provide a reflection gain with low power consumption compared to the transistor based circuits, we used the tunnel diode model AI201A Ga-As to design a low-power reflection amplifier. Figure 1(a) shows the I-V curve of the tunnel diode measured with a HP 4155A parameter analyzer. In order to obtain an accurate model of the tunnel diode characteristic, the S-parameters of the diode has been extracted using the TRL (Through-Reflect-Line) calibration method, Fig. 1(b). The reflection coefficient of the tunnel diode is $\Gamma_{TD} = (Z_{in}^{TD} - Z_0)/(Z_{in}^{TD} + Z_0)$ where TD denotes the tunnel diode, Z_{in}^{TD} is the input impedance of tunnel diode, and Z_0 accounts for the characteristic impedance of the connected load, which is usually $50\ \Omega$. In the negative differential resistance (NDR) region $Re(Z_{in}^{TD}) < 0$ which

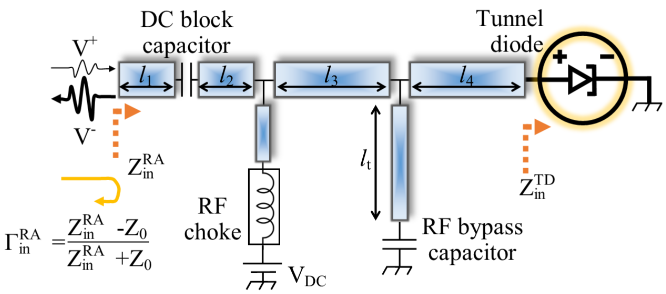

Fig. 2: Tunnel diode based reflection amplifier circuit diagram.

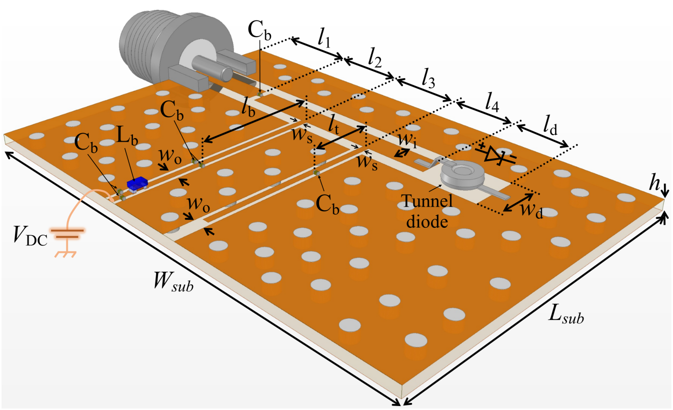

Fig. 3: Reflection amplifier layout. The dimensions in mm are: $l_1 = 7.5,\ l_2 = 5,\ l_3 = 5.6,\ l_4 = 4.5,\ l_d = 4.9,\ l_t = 3,\ l_b = 10,\ w_i = 1.8,\ w_s = 0.5, w_o = 1.1, w_d = 3.8,\ h = 0.812\ w_{sub} = 37$ and $L_{sub} = 25$. $C_b = 33$ pF and $L_b = 40$ nH.

leads to $|\Gamma_{TD}| > 1$. By matching the input impedance of the tunnel diode to a desired value, stability in the reflection gain can be achieved. The circuit diagram of the tunnel diode based reflection amplifier is shown in Fig. 2. The measured input impedance of the tunnel diode at the bias voltage $V_{DC} = 0.117$ V is $Z_{in}^{TD} = -2.56 - j13\ \Omega$ which is in the NDR region of the tunnel diode. This impedance is matched to Z_{in}^{RA} to reach a desired reflection gain and avoiding oscillation in the circuit. Active devices with input NDR are widely used in oscillator circuits. Thus to avoid triggering oscillations in the reflection amplifier, the condition $Re(Z_{in}^{RA} + Z_0) > 0$ must be satisfied. The matching circuit in Fig. 2, consisting of a shunt short-ended microstrip, is designed to match the input impedance of the reflection amplifier $Z_{in}^{RA} \simeq -35 - 20j\ \Omega$. This input impedance provides the reflection gain with a sufficient margin to prevent oscillation. The layout of the proposed reflection amplifier is shown in Fig. 3. Using a grounded co-planar waveguide (GCPW) transmission line helps to adjust the length of the stubs after fabrication. Figure 4 shows the simulation and measurement results of the fabricated circuit. Differences between simulated and measured results are attributed to fabrication errors as well as inaccuracies in the extracted values of the S-parameters of the tunnel diodes. These same reasons apply later on in Fig. 7. The source power P_{in} of the network analyzer (Agilent N5222A PNA) is set to -30 dBm. The power consumption is 178 μW for a 0.117 V DC bias voltage with a 1.5 mA forward current.

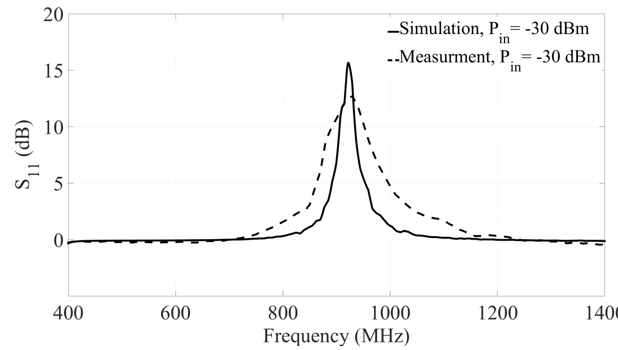

Fig. 4: Simulated and measured return gain of the reflection amplifier. $V_{DC} = 0.117\ V,\ I_{DC} = 1.5$ mA.

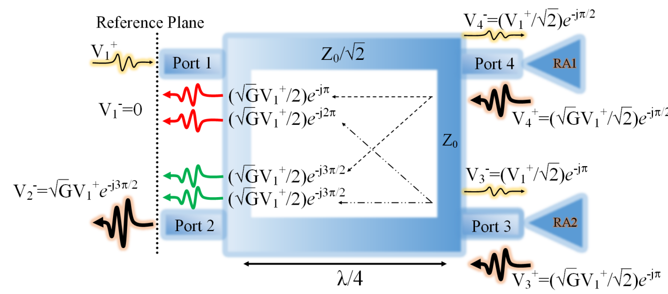

Fig. 5: Configuration of the bidirectional amplifier.

III. Bidirectional Amplifier

Two identical reflection amplifiers (RA_1 and RA_2) are integrated with a four-port BLC to build a bidirectional amplifier as shown in Fig. 5. Port 1 and port 2 are RF in/output and port 3 and port 4 are connected to the reflection amplifiers. We first derive the forward gain from port 1 to port 2, defined by $S_{21} = V_2^-/V_1^+\ |_{V_2^+=0}$. Figure 5 shows the diagram of the signals in a bidirectional amplifier. The incident signal V_1^+ is divided between port 3 and port 4 with the same amplitude and a 90° phase shift as V_3^- and V_4^-. The waves coming to port 3 and port 4 are reflected back to the BLC by RA_1 and RA_2 with equal return amplitude gain $\sqrt{G}$ as V_3^+ and V_4^+, respectively. Then V_3^+ and V_4^+ are divided between port 1 and port 2. As can be seen in Fig. 5, at port 1 the reflected signals are out of phase and cancel each other out while at port 2 they are in phase and add constructively with amplitude gain $\sqrt{G}$. The backward gain from port 2 to port 1, $S_{12} = V_1^-/V_2^+\ |_{V_1^+=0}$, can be derived in the same manner. The bidirectional amplifier in Fig. 5 amplifies the signal coming from both port 1 and port 2 simultaneously with power gain G.

Figure 6 shows the bidirectional amplifier layout. Meander lines are used in the BLC branches in order to shrink the circuit size. To increase the return loss of the bidirectional amplifier, the two reflection amplifiers should be identical. Separate DC bias sources and tunable stubs may be used to achieve identical frequency responses for the reflection amplifiers. Thus, the fabricated circuit can be tuned by changing the length l_t at the RA configuration, via a 33 pF capacitor connected to ground and tuning the bias voltage to optimize the in/output VSWR. Figure 7 shows the forward and backward transmission gains

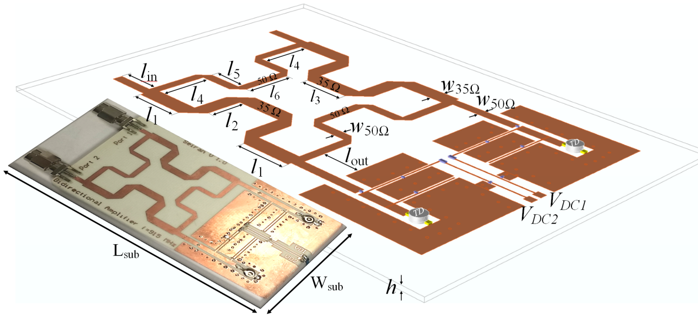

Fig. 6: Bidirectional amplifier layout. The dimensions in mm are: $l_{in} = 7.5$, $l_1 = 9.15$, $l_2 = 6.65$, $l_3 = 9.3$, $l_4 = 9.2$, $l_5 = 6.7$, $l_6 = 9.4$, $l_{out} = 7.55$, $W_{35\Omega} = 3.1$, $W_{50\Omega} = 1.8$, $L_{sub} = 76$, $W_{sub} = 47$.

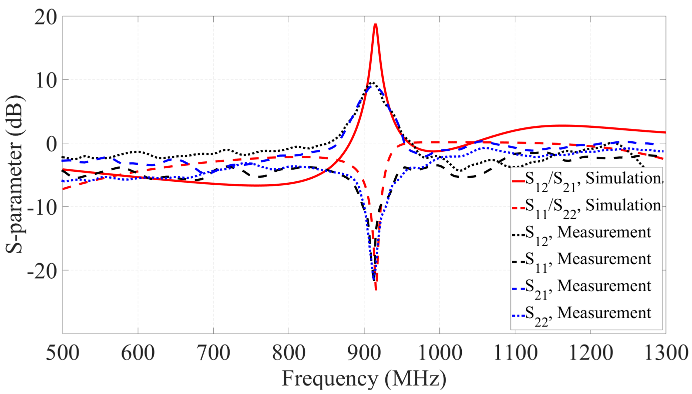

Fig. 7: The simulated and measured S-parameters of the proposed bidirectional amplifier. $P_{in} = -30\ dBm$, $P_C(DC\ power\ consumed) = 356\ \mu W$, $V_{DC1\&2} = 0.114\ V$.

(S_{21}, S_{12}) of the proposed bidirectional amplifier for the input power of -30 dBm. The reflection coefficient of port 1 and port 2, (S_{11}, S_{22}) is also shown in Fig. 7. Transmission gain of 9 dB and return loss of 22 dB at 915 MHz are measured.

In order to investigate the 1 dB compression point (P1dB) and the output power vs. the incident power, the measurements are done with a Keysight FieldFox N9916A microwave analyzer, using its minimum input power level $P_{in,min} = -45$ dBm and a maximum input power level $P_{in,max} = -17$ dBm. The transmission gain S_{21}, phase $\angle S_{21}$ and the reflection coefficient S_{11} of the proposed bidirectional amplifier are shown in Fig. 8. The operation bandwidth ($|\Gamma| > 0\ dB$) is around 100 MHz and the total power consumption is 356 μW. The bandwidth of the bidirectional amplifier mostly depends on the bandwidth of the tunnel diode, whose bandwidth is limited by its parasitic elements. Fig. 8 shows that by increasing the input power the gain decreases due to the tunnel diode whose behavior is greatly affected by its bias point. Therefore, large input power values can cause a shift of the tunnel diode bias point. In turn, changes of the bias point can modify both the input impedance and the gain of the reflection amplifier and, consequently, the bidirectional amplifier gain.

IV. Conclusion

A low-power reflection amplifier by means of a tunnel diode has been proposed. Biasing the tunnel diode with DC voltage as low as 0.117 V, drives it into its NDR region. Two reflection amplifiers with similar performance are integrated with a BLC to form a bidirectional amplifier. The outcome is a low-power switchless bidirectional amplifier that can be used in retro-directive arrays and RFID applications. The applied bias voltage is low enough to be extracted by a photo-voltaic cell. Note that the degree of similarity of the two reflection amplifiers has a major effect on the final performance.

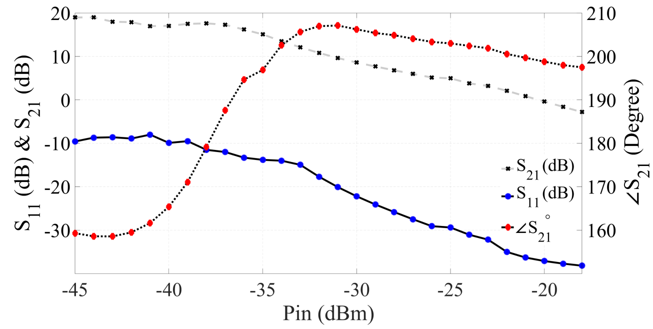

Fig. 8: The S-parameter of the bidirectional amplifier based on the incident power level.

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