Direct-Signal Modulation Using a Silicon Microstrip Patch Antenna

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***Abstract*—In this paper, a microstrip patch antenna is fabricated directly onto a high-resistivity silicon substrate without an insulating barrier, thereby forming a distributed Schottky diode between the patch radiator metallization and ground plane. By applying dc bias control to the patch metallization, direct amplitude modulation of a CW microwave carrier can be achieved. Experimental results are presented that show the far-field radiation characteristics of the structure and its response to applied base-band modulation signals. Also direct base-band signal detection using the patch antenna is discussed.**

I. INTRODUCTION

THE need for low-cost novel antenna structures for portable wireless communication systems at microwave frequencies is becoming a commercial imperative [1], [2]. This paper describes the operating characteristics of a microstrip patch antenna constructed on a high-resistivity silicon (HRS) substrate. Compared with previously published self-mixing active antenna that use a discrete mixing diode, e.g., [3], the antenna structure in this paper concurrently embodies an integrated antenna with diode functionality making it useful for direct encoding of base-band data onto an RF carrier.

The integral modulator/patch antenna thus formed was constructed on a p-type $\langle 100 \rangle$ orientation 10 KΩ-cm HRS substrate, minimum carrier lifetime 6200 μS and doping concentration 3×10^{12} cm^{-3}. The wafer thickness and the dimensions of the patch are shown in Fig. 1. A 1.3-μm-thick aluminum layer was evaporated in a 1×10^{-6} Torr vacuum. Both sides of the wafer are metallized and the top side patterned in order to create a microstrip patch antenna. The relative dielectric constant of the material is 11.9 and for the metallization type used here the average conductivity of the metal in the range 1–40 GHz is 2.3×10^{7} S/m and substrate loss tangent is approximately 1.63×10^{-3} [4].

The silicon process used here is unlike previous HRS microstrip realizations [5], [6] since no insulating SiO_2 layer is incorporated beneath the upper conductor. In addition, in this paper, the patch pattern is produced on the polished side of the wafer with the ground plane on the etched side. The consequence of these actions is that intimate contact between the metal patch pattern and the silicon substrate exists on the polished side of the wafer. This contact enables a metal semiconductor barrier to be created [4]. While the larger area forming the ground plane has less intimate contact with the silicon wafer since it is formed on the etched side. This contact is equivalent to many metal-semiconductor barriers in shunt connection. This results in an ohmic contact being formed. The overall effect of these metal/substrate connections is to form a distributed rectifying diode between the patch and the ground plane, Fig. 1. Thus, the prospect for altering the dc bias applied to the patch antenna, hence antenna radiation behavior exists. These effects will now be investigated.

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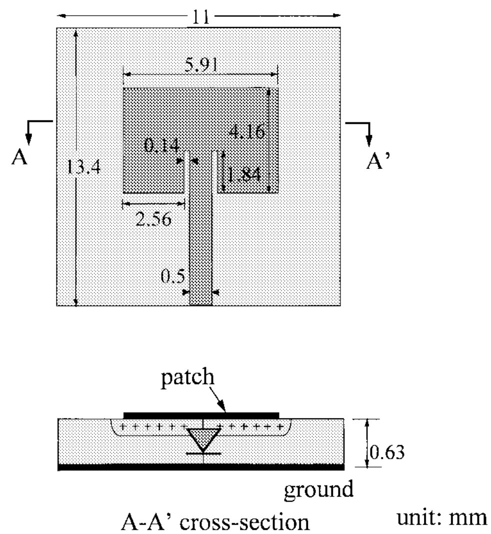


Fig. 1. Configuration of a silicon direct modulation patch antenna.

II. ANTENNA CHARACTERISTICS

The current–voltage characteristic for the antenna with a dc positive bias applied between the patterned antenna patch metallization and the grounded backplane is shown in Fig. 2. For this structure, the negative bias leakage current is small (less than 20 μA for a reverse bias voltage up to -10 V). From Fig. 2 the nonlinear *I–V* characteristic of the structure is seen to operate in series with an approximate 50-ohm resistance at a forward diode bias voltage of 3.3 V due to the substrate resistance and ohmic contact formed between the backplane metallization and the semiconductor substrate interface. From this graph it is seen that diode action is available for direct modulation control purposes.

In order to test this hypothesis, the input reflection coefficient (S_{11}) of the antenna (nominal design frequency 10.0 GHz) under different bias voltages was measured over the frequency range of 7–13 GHz, Fig. 3. It can be seen from Fig. 3 that the dc bias level not only influences the

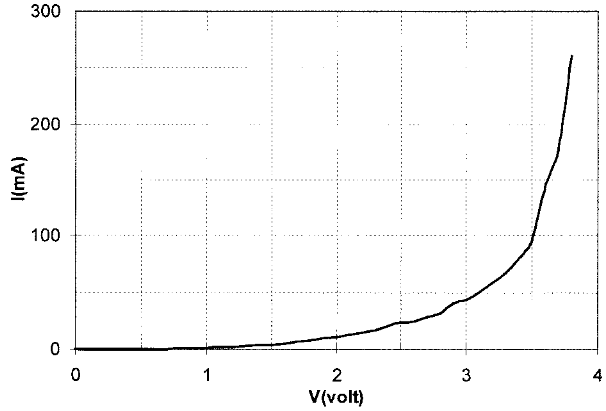


Fig. 2. Antenna dc current–voltage characteristic.

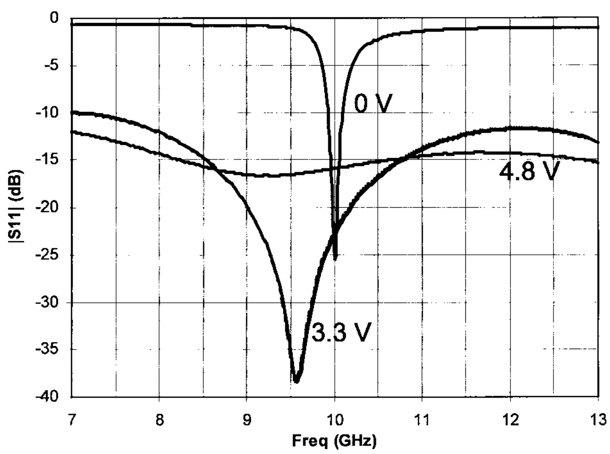


Fig. 3. Antenna reflection coefficient with dc bias.

antenna input match but it also changes the antenna's resonant frequency, this means we can tune the antenna's working frequency by changing the dc bias applied to it within a certain range while still maintaining a reasonable radiation power level (Fig. 5) and a good input match. The resonant frequency is 10.09 GHz and for a VSWR of 1.4 the bandwidth of the antenna is 75 MHz at 0-V dc bias. When a 1-V bias is applied, the resonant frequency decreases to 9.94 GHz, i.e., a frequency shift of 150 MHz.

Next, the boresight radiated power as a function of dc bias was measured, these results are shown in Fig. 4. From Fig. 4 it can be seen that the radiated power level decreases with increased applied bias voltage. This is due to two effects, the principal one is the dc bias controlled increased diode controlled leakage current between the patch and the ground plane due to forward bias diode action. Also from Fig. 3, S_{11} reduces as a whole with the increase of bias voltage. Due to attenuation caused by diode leakage current between the patch and the ground plane, the patch resonance phenomena becomes less pronounced and finally disappears at a bias voltage around 4.8 V at which point the circuit works in a similar fashion as an attenuator rather than as an antenna. The second effect is due to small variation of antenna resonant frequency with dc bias which generates a mismatch in the neighborhood of the resonant frequency.

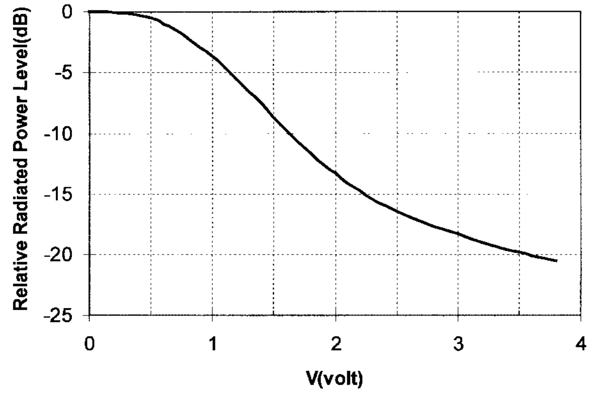


Fig. 4. Relative radiated power level versus dc bias.

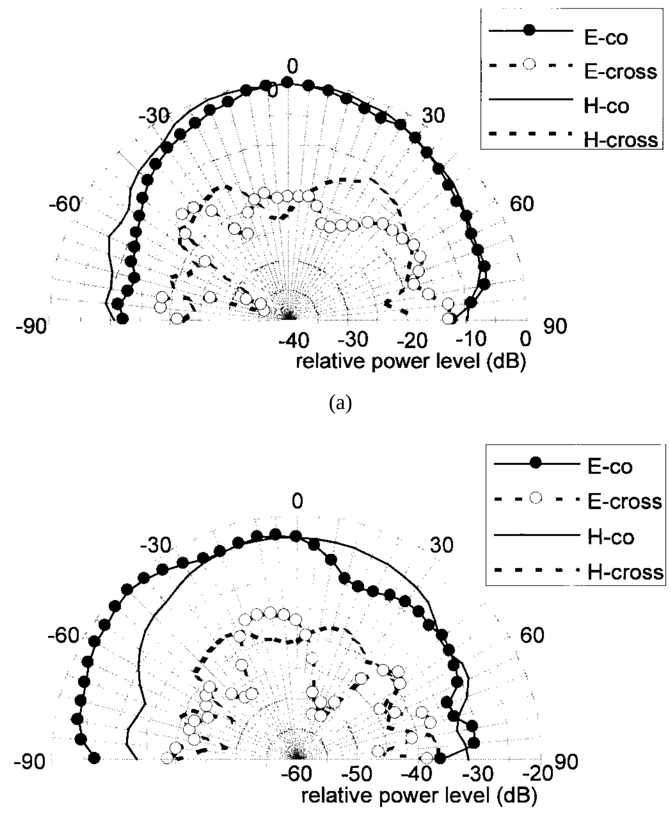
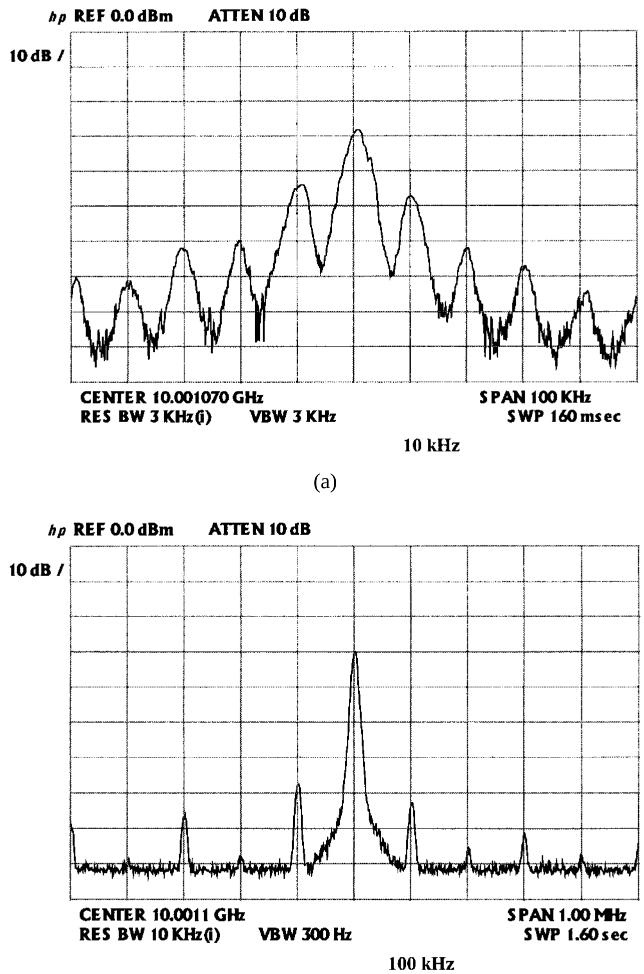


Fig. 5. Measured radiation patterns as afunction of dc bias. (a) 0-V bias $f_0 = 10.09$ GHz. (b) 4.4-V bias $f_0 = 10.09$ GHz.

Next, the far-field radiation pattern under two extreme dc bias conditions—0-V diode off and 4.4-V diode on—were measured and are presented in Fig. 5. It can be seen that the radiation patterns of the antenna under 4.4-V bias are similar to those under 0-V bias. However, the boresight radiated power levels under 4.4-V bias are approximately 21 dB less when compared to those with measured with 0-V bias applied. These observations suggest that by changing the bias voltage applied to the patch antenna, direct base-band data encoding by way of amplitude modulation of the RF carrier can be achieved.

III. Modulated Signal Response

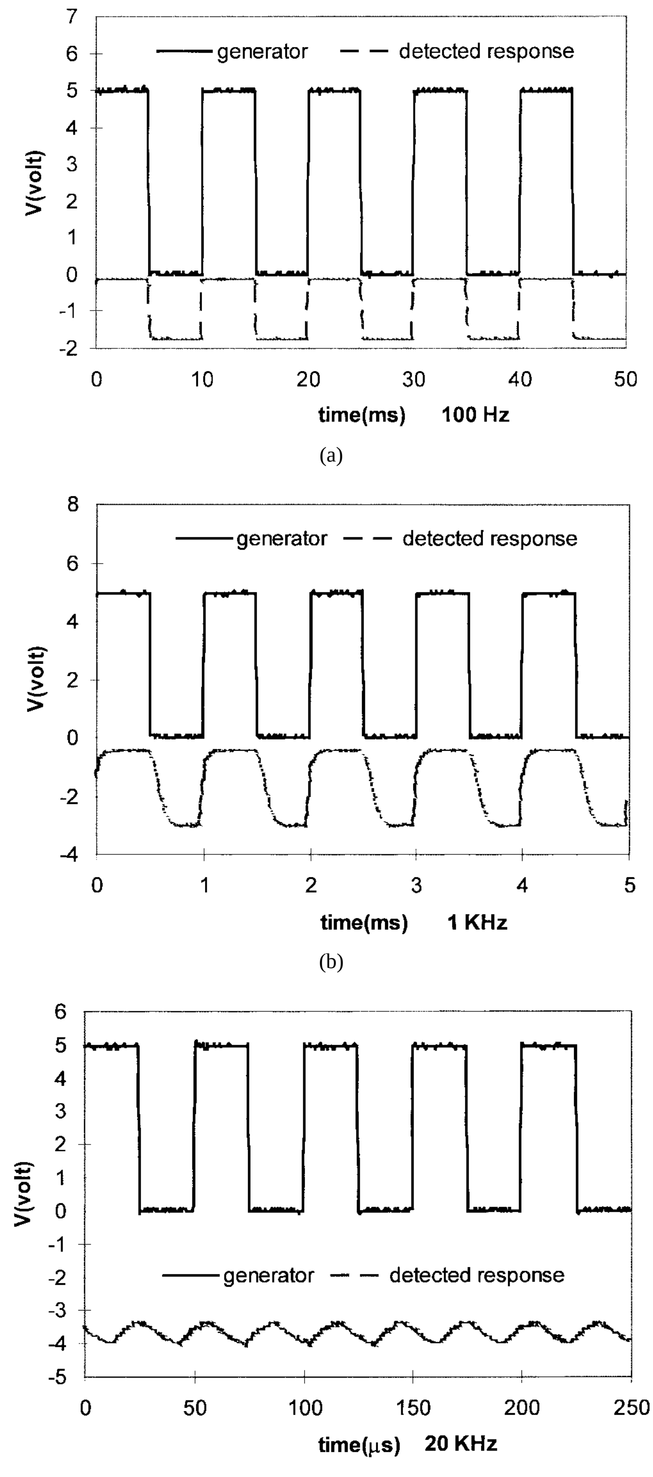
Fig. 6 shows the spectrum of the transmitted signal when square wave modulated with a 5-V (peak-to-peak) unipolar



(a)

(b)

Fig. 6. Spectra of the modulated RF signals. (a) 10 kHz. (b) 100 kHz.



(a)

(b)

(c)

Fig. 7. Detected signal. (a) 100 Hz. (b) 1 kHz. (c) 20 kHz.

signal at 10 and 100 kHz. These responses show that direct dc bias modulation of the 10.09 GHz carrier is occurring. The upper side band of the amplitude modulated waveform suffers a higher degree of attenuation than the lower sideband. This effect is due to the VSWR dependency on bias level observed in Fig. 3. In addition, low-level intermodulation effects as a result of diode mixer action can also be seen to occur between the expected square wave harmonic sidebands. Harmonic filtering is also occurring and is now discussed in the context of the signal detection properties of the antenna.

IV. Homodyne Signal Detection

In this section, square waves are used as modulating signals in order to test the modulation speed and transmission characteristics of the antenna. In order to restore the square wave signal modulation without distortion, many harmonics with correct relative amplitude and phase information is required. In the experimental work presented here, a negative bias crystal detector (HP423A) was used to detect a low-frequency amplitude modulated square wave after it had been applied as a dc bias switch to the new antenna structure in order to control a 10.09-GHz carrier signal. The detector was connected to the output of a pyramidal horn placed in the far field of the antenna under test. A carrier signal level of 13 dBm was used to excite the patch antenna and a 20-dB wide-band amplifier was placed at the detector output.

It can be seen that from Fig. 7 that at a modulation frequency of 100 Hz there is no distortion in the detected signal waveform when compared with the original input square wave. At 1 kHz the detected signal waveform still tracks the original input square wave but now exhibits some distortion.

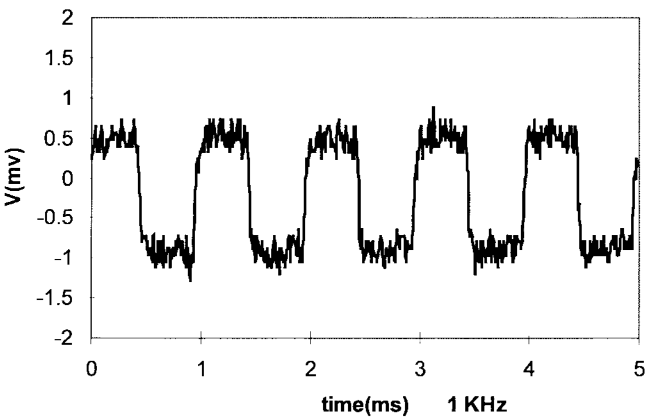


Fig. 8. Patch antenna direct detection response.

With an increase of modulating signal frequency to 20 kHz, the waveform of the detected signal becomes distorted and attenuated. This frequency limitation is mainly due to two effects, the principal one is the diode turn-off period limitation dominated by the long carrier lifetime (larger than 6200 μm as quoted by manufacturer) associated with the HRS substrate used to construct the antenna. An analytical formula for the diode turnoff period [7]

$$t_{\text{off}} = \frac{1}{2}\left(\frac{I_F}{I_{R,\text{ave}}}\right) \cdot \frac{W_B^2}{D_p} \quad \text{for } W_B \ll L_p$$

where

- I_F forward current, $I_{R,\text{ave}}$ is average reverse current;
- W_B separation between contact and injection junction;
- D_p diffusivity of holes;
- L_p diffusion length of holes

is used in this paper and is found to yield a value of 0.17 mS. This agrees well with the 0.2 mS measured turnoff time for the 1-kHz square-wave modulation response shown in Fig. 7(b). The second effect is due to the diode capacitive parasitic caused by the large diode volume under the patch antenna. The average capacitance is measured to be around 400 pF with a test signal frequency of 10 kHz. When combined with the resistance (4.1 kΩ) of the structure, this gives a cutoff frequency of 97 kHz, which suggests that the turnoff period is the dominant factor.

V. The Patch as Detector

Based on the diode effect of the patch antenna, the patch can also be used as a detector. A 1 kHz square wave modulated 10.09 GHz microwave signal at 14 dBm was connected to the patch and the resulting detected signal displayed on an oscilloscope. Fig. 8 shows the waveform of the detected square wave. The minimum detectable signal at 1-kHz fundamental frequency was measured using a wave analyzer to be −46 dB in a 3-Hz bandwidth.

VI. Conclusion

The basic performance characteristics of a novel modulator/detector silicon microstrip patch antenna capable of direct AM encoding/decoding of base-band data applied as dc bias was presented in this paper. By direct aluminum metallization deposition onto silicon substrate material, a distributed rectifying diode was formed between the microstrip patch metallization and the ground plane. It was shown that the major antenna characteristic—radiated power level—can be directly controlled by the dc bias voltage applied to the distributed diode intrinsically formed by the antenna on silicon structure. This allows direct-signal detection showed that direct amplitude modulation of continuous wave RF signals applied to the patch. Far-field measurements show that dc bias control of the patch antenna allows it to act as an electronic attenuator, thereby reducing the radiation level without significantly changing the radiation patterns associated with the patch antenna.

It was also shown that since the antenna is constructed on a p-type 16 KΩ-cm HRS substrate, the minimum carrier life time of 6200 μS of this material is the principal limiting factor on the upper modulation frequency response of the antenna.

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