III. Conclusion

The potential distribution through a thick conducting rectangular aperture is studied using the Fourier-transform and the mode-matching technique. The normalized electric polarizability is insensitive to a change in d/a when $d/a > 0.5$. The solution is represented in rapidly-convergent series form which is numerically very efficient.

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Photovoltaic-FET for Optoelectronic RF/μwave Switching

C. K. Sun, R. Nguyen, C. T. Chang, and D. J. Albares

Abstract—**A photovoltaic-FET (PV-FET) is demonstrated for RF/μwave switching with performance improved over other optoelectronic switches reported while operating with 10-100 times less optical power. The PV-FET characteristics were 3 Ω on-resistance, > 30 MΩ off-resistance under <1 mW optical power, and 300 fF switch capacitance. This PV-FET was inductor tuned at 790 MHz and 7.4 GHz to enhance isolation, intended for reconfigurable antenna applications. The measured insertion loss and isolation agree well with those from theoretical calculation and numerical circuit simulation based on the switch parameters. The measured switch rise and fall times were 20 μs and 2 μs, respectively. Controlled by light via optical fiber, the PV-FET can be used for remote RF/μwave switching control with no electrical bias, complete electromagnetic, and good thermal isolation.**

I. Introduction

Optically activated electronic switches or optoelectronic (OE) switches have long been investigated for generating and sampling ultrafast electrical pulses [1]–[3]. Recently, OE switches controlled by light via optical fibers and without electrical bias have been considered for RF/μwave (abbreviated RF hereafter) switching due to unique and often decisive advantages of the electromagnetically and thermally isolated control lines. Other appealing features offered by optical fibers are small size, lightweight, and low loss (long distances). Potential applications of such an OE switch include reconfigurable antennas [4], programmable antenna feeds and tuned networks, and switching within cryogenic electronic circuits [5]. The OE switch configuration and characteristics required in each application vary. Typical OE switches for reconfigurable antennas are used in series connection between antenna segments. The required characteristics are low on-resistance R_{on} (<5 Ω), high off-resistance R_{off} (>10 kΩ), low capacitance C (<300 fF, for C to X band), bias-free operation, and low optical control power. Needed switching speeds range from ms to ns and power handling ranges from μW to hundreds of watts.

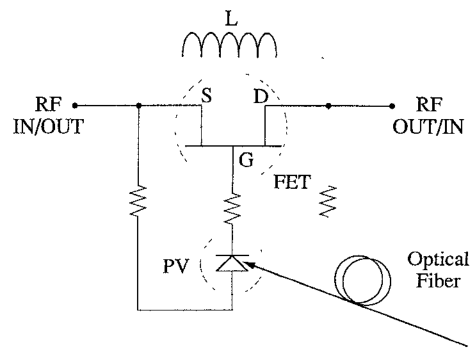

Fig. 1. Circuit schematic of the PV-FET switch with a depletion-mode FET. An inductor L in parallel with the FET may be used to enhance the isolation at the vicinity of the tuned frequency. Without the tuning inductor, a resistor between the gate and drain is used for electrical bias.

OE switches such as photoconductor [6], [7], surface-depleted optical FET [8], [9], and direct optically illuminated FET [10] have been investigated, but they lacked the switch characteristics mentioned above and generally required high optical power. A photoconductive switch under high optical power (>50 mW) obtained low R_{on} of 2 Ω, but suffered from low R_{off} ($\leq$1 kΩ) and millisecond switching time. The surface-depleted optical FET was activated by low optical power ($\sim$1 mW) but had low RF power handling capability ($\sim$1 mW). The direct optical illuminated FET can be used as an optically controlled switch but requires external electrical gate biasing (via metal wire) which compromises electromagnetic and thermal isolation.

A photovoltaic-FET (PV-FET) switch has been reported with R_{on} of 65 Ω and C of 65 fF [9]. We report a PV-FET with improved performance and the introduction of tuning to enhance isolation as a series switch for reconfigurable antennas [4], [9]. We obtain $R_{\text{on}} \approx 3\ \Omega$, $R_{\text{off}} > 30$ MΩ under <1 mW optical power, and $C \approx 300$ fF. These parameters are consistent with the measured insertion loss of 0.33 dB and the untuned isolation of 17 dB at 790 MHz. Tuning out the FET capacitance at 790 MHz gives an isolation of 57 dB and tuning at 7.4 GHz gives 23 dB isolation. The switching speed of the tuned PV-FET at 790 MHz is measured to be 20 μs rise time and 2 μs fall time. The power handling capability is estimated to be 0.12 W. Since FET's are excellent voltage-controlled RF switches with high gate-impedance requiring minimum control current or power, the overall PV-FET switch characteristics are superior to reported OE switches while requiring 10 to 100 times less optical power.

II. Device and Experiment

Fig. 1 depicts the PV-FET schematic with a depletion-mode FET. This PV-FET switched by illuminating the PV cell can be used as a series switch for reconfigurable antennas [4], [9]. The switch is on (closed) without illumination and the switch is off (open) with illumination to generate a photo-voltage exceeding the FET pinch-off voltage. The floating circuit illustrated in Fig. 1 is needed to obtain control voltage to the FET switch without connection to the electrical

Manuscript received November 6, 1995; revised June 14, 1996.
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Publisher Item Identifier S 0018-9480(96)06915-3.

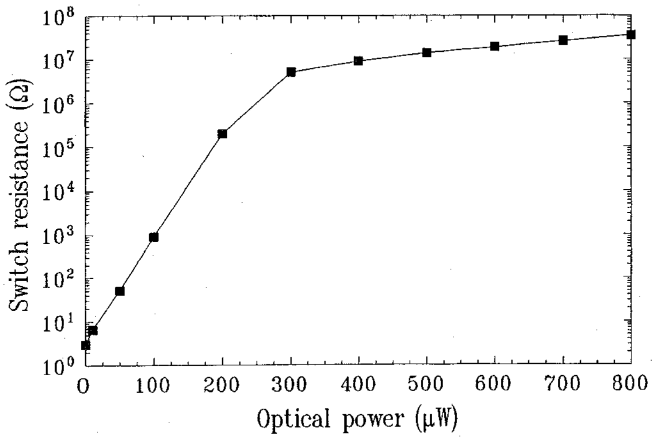

Fig. 2. The measured dc switch resistance as a function of control optical power.

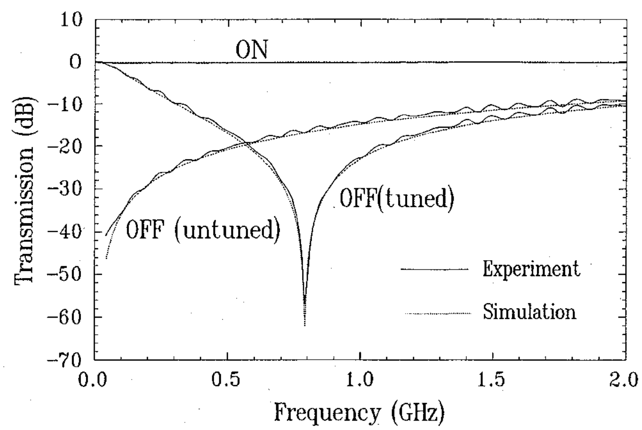

Fig. 3. Insertion loss and isolation measured from 50 MHz to 2 GHz for both untuned and tuned (790 MHz) PV-FET's. Solid lines represent measured results and dotted lines represent simulated results.

ground. Resistors between the PV cell and the FET reduce signal leakage through the control circuit in the off-state. At high frequency, the source-drain capacitive feedthrough limits the isolation as in all semiconductor switches. Tuning by adding an inductor in parallel resonance [12] with the FET capacitance as shown in Fig. 1 can be used to enhance the off-state isolation in the vicinity of the tuned frequency.

To investigate the switch characteristics, we built a hybrid PV-FET with a commercial 12-volt GaAs photovoltaic cell and an InP depletion-mode JFET [13]. This JFET had $R_{\text{on}} \approx 3\ \Omega$, $R_{\text{off}} > 500\ \Omega$ at a soft gate pinch-off voltage ~7 V, $R_{\text{off}} > 30\ \text{M}\Omega$ at a complete gate pinch-off voltage $\approx$ 10 V, and drain-source saturation current $I_{\text{dss}} \approx 0.7$ A. An optical fiber with 100-μm-core diameter transmitted the control signal from a laser diode of 0.8 μm wavelength to the PV cell having an active area of 7 mm^2. Fig. 2 shows the switch dc resistance measured as a function of optical power on the PV cell; a few hundred microwatts changed resistance from 3 Ω to >1 MΩ.

The PV-FET was packaged on a 50-Ω test fixture to measure its RF performance. Multi-bondwires were used to connect the FET to the transmission lines for reducing parasitic resistance and inductance. Fig. 3 shows the insertion loss (IL) and the isolation of both tuned and untuned PV-FET switches as a function of signal frequency. The IL was 0.33 dB and C = 300 fF estimated from the untuned isolation of 17 dB at 790 MHz. The PV-FET was tuned at 790 MHz with an inductor of 130 nH to enhance isolation from the untuned 17 dB to

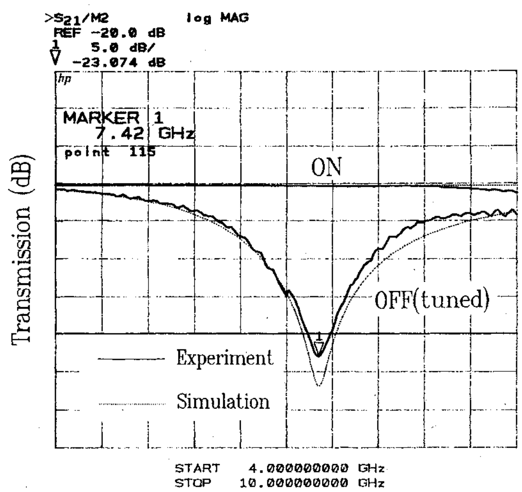

Fig. 4. Insertion loss and isolation measured from 4 GHz to 10 GHz for the PV-FET tuned at 7.4 GHz. Solid lines represent measured results and dotted lines represent simulated results.

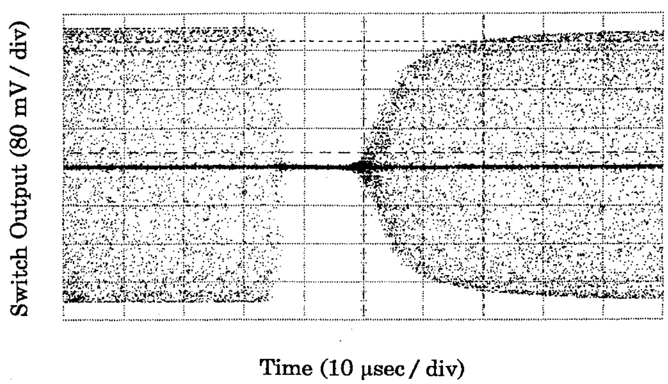

Fig. 5. The switch rise time (~20 μs) fall time (~2 μs) measured, respectively, with the digital oscilloscope synchronized at falling and rising edges of the control signal and the unsynchronized switch output at 800 MHz recorded in the persistent mode.

57 dB at the tuned frequency. The tuned switch operated from 580 MHz to 1070 MHz with ≥20 dB isolation. The PV-FET was also tuned at 7.4 GHz as shown in Fig. 4; we measured an IL of 0.33 dB, a maximum isolation of 23 dB, and a bandwidth of 300 MHz with ≥20 dB isolation.

The switching speed of the tuned PV-FET was measured by observing switch rise and fall times as the PV cell was illuminated by 1 mW optical pulses with rise and fall times <1 μs. The switch input was from an 800 MHz sinewave generator and the switch output was displayed on a digitized sampling oscilloscope. Fig. 5 shows the superposition of two switching outputs with the oscilloscope triggered by the rising and falling edges of the electrical pulses. The measured rise (switch off-to-on) time was about 20μs and the fall (switch on-to-off) time was about 2 μs.

III. Analysis and Discussions

The PV-FET has demonstrated excellent RF switching characteristic with minimum control optical power, compared with conventional photoconductive switches. The contrast stems from different switching control mechanisms. For the photoconductive switch, the conductivity is directly proportional to the photocarrier density and high optical power (0.1 W to MW) is commonly required to achieve low R_{on} [7]. Materials with long carrier lifetime are used to reduce the optical power requirement, at the expense of switching speed. As for the PV-FET, conduction of the JFET channel is controlled by the gate depletion via the external PV voltage. Since the gate resistance R_g of the JFET is greater than 0.1 MΩ, 300 μW of optical power at 0.8 μm wavelength was sufficient for the PV cell to generate a photocurrent greater than 100 μA and a photovoltage higher than 10 V to pinch off the FET switch completely.

In a simplified equivalent circuit model, the PV-FET in the on-state can be represented by the FET's drain-source resistance ($= R_{on}$), the sum of the channel resistance R_c and series resistance R_s. The PV-FET in the off-state can be represented by R_s in series with C which includes the FET's drain-source contact capacitance and drain-gate-source junction capacitance. With the switch in series connection between a load Z_0 and a RF source with output source impedance Z_0, the IL is [14]

$$IL = 20 * \log\left(1 + \frac{R_{on}}{2Z_0}\right) \quad (1)$$

and the isolation is

$$\text{Isolation} = 10 * \log\left[1 + \left(\frac{1}{4\pi f Z_0 C}\right)^2\right]. \quad (2)$$

For an FET tuned with inductor L and a series parasitic resistance R_L, the switch off-impedance is increased from $1/(2\pi f_0 C)$ to $L/[C(R_s + R_L)]$ at the tuned frequency $f_0 = 1/2\pi\ (LC)^{0.5}$. The maximum isolation at f_0 is [15]

$$\text{Isolation} = 20 * \log\left[1 + \frac{R_{on}}{2Z_0}\left(\frac{f_c}{f_0}\right)^2\right] \quad (3)$$

where the cutoff frequency f_c a figure of merit for tuned switches, is defined as

$$f_c = \frac{1}{2\pi C\sqrt{R_{on}(R_s + R_L)}}. \quad (4)$$

The JFET had a channel width, length, and thickness of 1 mm, 2 μm, and 0.3 μm, respectively. With a doping concentration of 1.5×10^{17}, the channel resistance R_c and the series resistance R_s are estimated to be 1 Ω and 2 Ω, respectively. From (1) to (4), the calculated IL at a signal frequency of 790 MHz is 0.26 dB, the untuned isolation is 17 dB, and the tuned isolation is 64 dB with R_L of 1.3 Ω. The tuned isolation at 7.4 GHz is calculated to be 28 dB with R_L of 0.1 Ω. Based on the equivalent circuit model and the estimated device parameters, Figs. 3 and 4 also showed the simulated isolation and its frequency dependance for the tuned PV-FET switch. Good agreement between the measured and simulated results is obtained.

The switch rise time of 20 μs is primarily determined by the circuit time 2.2 $R_g C_p$ (~22 μs) responsible for discharging the PV cell through R_g (~0.1 MΩ) and a PV capacitance C_p (~100 pF) much larger than FET gate capacitance C_{gs} and C_{gd}. The switch fall time is just the photovoltage build-up time [16] across the PV cell and is estimated to be $t_f \approx (100\ \text{pF} \times 10\ \text{V})/0.5\ mA = 2\ \mu s$, assuming 0.5 mA photocurrent is obtained from the PV cell with 1 mW optical activating power. Faster fall times have been observed experimentally by increasing the optical power. Shunt resistors in parallel connection between the FET gate-source and/or gate-drain can reduce the effective gate resistance R_g and the corresponding switch rise time, at the expense of increasing optical power. Another approach to increase the switching speed is to reduce the PV capacitance, e.g., both rise time and fall time can be improved 100 times if C_p is reduced from 100 pF to 1 pF by decreasing the present PV active area from 7 mm^2 ^{7} to 7×10^{-2} mm^2.

The on-state power handling capability is mainly limited by its saturation current I_{dss}, while the off-state power handling is limited by its maximum voltage swing $V_b - V_p$ between source/drain to gate. Here V_b and V_p are FET breakdown voltage and pinch-off voltage, respectively, and their values depend on the degree of isolation. With the FET switch biased at the voltage $(V_b + V_p)/2$ in a transmission line of $Z_0 \gg R_{on}$, the on-state and off-state power handling are, respectively, estimated as [15], [17]

$$P_{on} = \frac{I_{dss}^2 Z_0}{2} \quad (5)$$

and

$$P_{off} = \frac{(V_b - V_p)^2}{8Z_0}. \quad (6)$$

As a result of doubling the input voltage due to complete impedance mismatch for the series switch with $R_{off} \gg Z_0$, the P_{off} in (6) is four times smaller than normally expected [17]. For the present InP FET switch in a $Z_0 = 50\ \Omega$ system with $I_{dss} = 0.7$ A and $V_b - V_p = -7$ V for 20 dB isolation, the power handling capability estimated from (5) and (6) is $P_{on} = 12.5$ W and $P_{off} = 0.12$ W. Since the concept of the PV-FET is generic and the InP FET used in this study was designed for amplification rather than for switching applications, the PV-FET RF performance can be improved by optimizing the FET geometry, channel doping, and thickness.

IV. Summary

We report improved PV-FET switches under control optical power <1 mW for RF switching with 3Ω on-resistance, greater than 30 MΩ off-resistance, and 300 fF switch capacitance. It has the advantage of low on-resistance (3 Ω) and high off impedance obtained by reducing capacitive feedthrough via tuning. The rise and fall times are 20 μs and 2 μs, respectively; both can be improved by reducing the PV capacitance. The measured insertion loss of 0.33 dB, the tuned isolation of 57 dB at 790 MHz, and the tuned isolation of 23 dB at 7.4 GHz are consistent with both theoretical calculation and numerical circuit simulation based on the switch parameters.

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