A Monolithic Integrated Millimeter Wave Transmitter for Automotive Applications

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Abstract—**An integrated transmitter at 80 GHz is presented. This device finds many applications in civil sensor and communication systems, and is employed in automotive applications. The device consists of an IMPATT diode and a slotted patch resonator. The resonator acts simultaneously as an antenna. The resonator impedance seen by the IMPATT diode is calculated by means of a full wave analysis and the matching of the IMPATT diode is investigated using a large signal analysis. The transmitter devices have been fabricated employing a SIMMWIC (silicon millimeter wave integrated circuit) fabrication process and deliver a radiated power of up to 1 mW at 79 GHz. An excellent carrier-to-noise ratio of 81.7 dBc/Hz at an offset of 100 kHz has been achieved. The deviation of the measured values from the theoretically predicted values of frequency and power is −5.9% and −1.5 dB, respectively.**

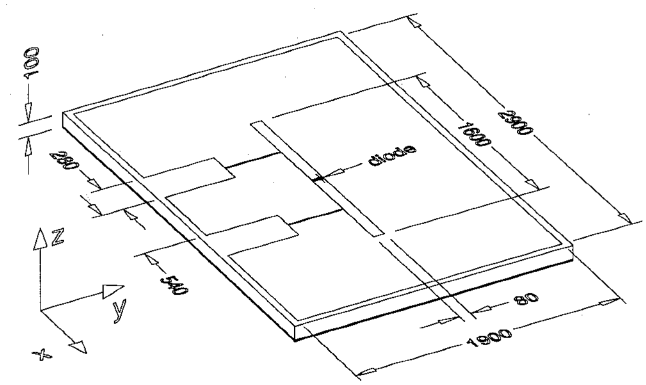

Fig. 1. Layout of the integrated transmitter.

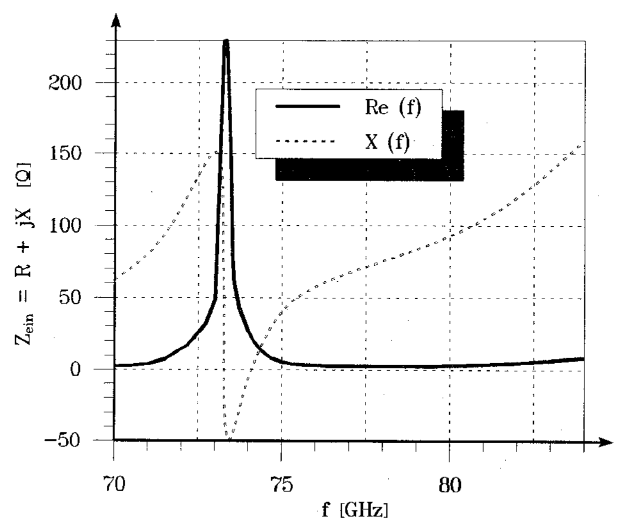

Fig. 2. Impedance versus frequency seen by the IMPATT diode.

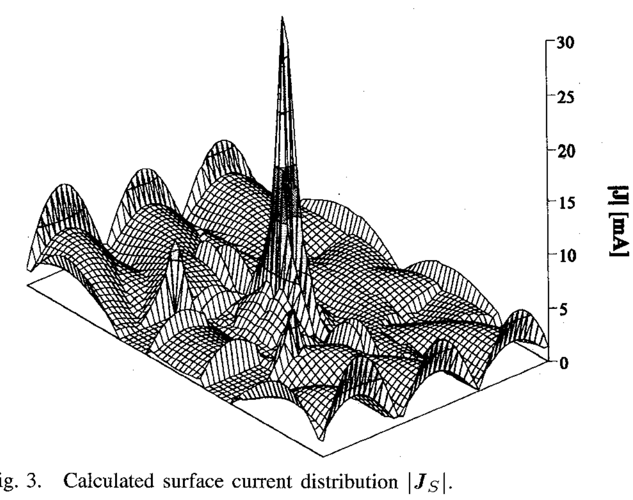

Fig. 3. Calculated surface current distribution $|J_S|$.

I. Introduction

Monolithic millimeter wave integrated transmitters and receivers are key elements of sensor systems for automotive applications. These sensor systems may be used for speed measurement, side crash detection, or evaluation of the road condition. The transmitters consist of an active element such as an IMPATT diode and an integrated resonant structure. In order to minimize the required chip dimensions, the resonator simultaneously acts as an antenna. Monolithic millimeter-wave IMPATT oscillators have been fabricated on GaAs [1], InP [2], and Si [3] but the matching of the low-impedance IMPATT diode in a planar configuration is critical and requires careful optimization of diode structure, geometry and resonator layout. By use of resonator layouts based on planar full wave slot antennas the impedance requirements are met, if the substrate is ungrounded [4], or if the substrate is grounded and about one half electrical wavelength thick [5]. On ungrounded silicon substrates in an upside-down configuration a radiated output power of 4.4 mW at 89 GHz has been achieved with integrated IMPATT diode transmitters [3]. On thin grounded substrates the strong excitation of the parallel plate waveguide mode by a simple slot resonator makes an impedance matching of the IMPATT diode impossible. However, using a thin grounded substrate would improve the thermal stability of the oscillator substantially.

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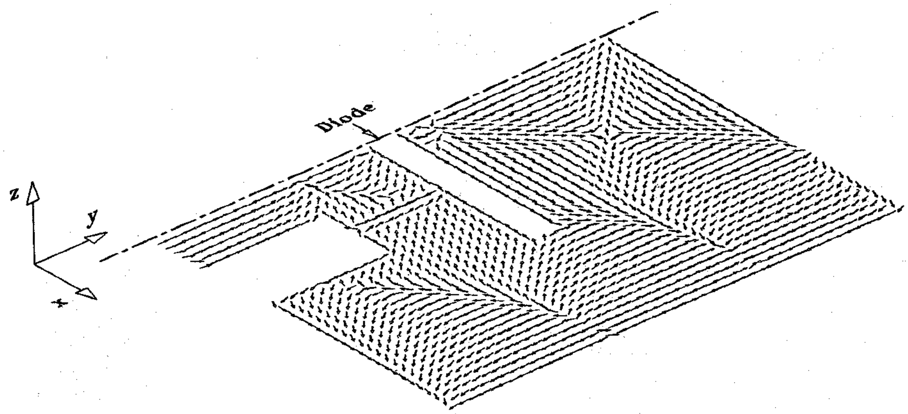

Fig. 4. Direction of the calculated current distribution.

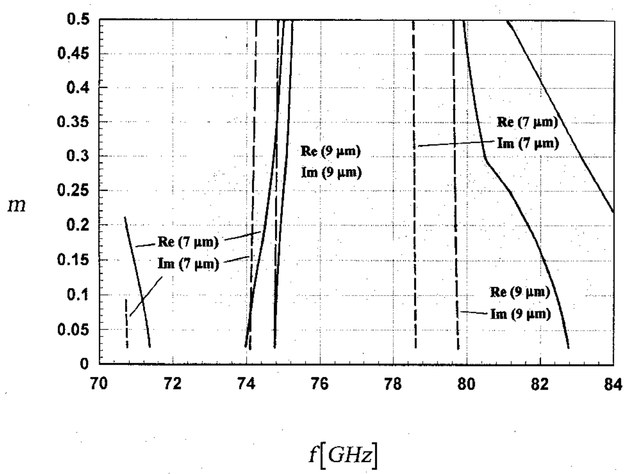

Fig. 5. Impedance in the modulation-frequency domain.

In this paper we present theoretical and experimental results of IMPATT oscillators based on a modified resonator layout. In Fig. 1 the layout of the integrated transmitter is depicted. Basically, the passive structure consists of a microstrip patch resonator, which is fed by a slot resonator located in the center of the patch. The patch resonator is 2.97×1.97 mm^2 in size. The slot is 1.6 mm long and 80 μm wide. At 75 GHz the slot length is about one electrical wavelength. The IMPATT diode has been placed in the center of the slot. The silicon substrate is 100 μm thick. This configuration combines several advantages: The impedance requirements of the IMPATT diodes are met even on thin grounded substrates. Thus, an efficient heat sink can easily be applied at the grounded side of the substrate. The slot resonator is a coplanar structure and, thus, compatible to monolithic integration of the IMPATT diode, i.e. no via holes are needed.

II. Analysis of the Impedance Matching

We calculated the impedance seen by the IMPATT diode and the surface current distribution on the patch using a full wave analysis based on the method of moments in the spectral domain.

In contrast to the approach based on the magnetic field integral equation (MFIE) for the modeling of slot resonators embedded in a metal plane of infinite extent, here the electrical field integral equation (EFIE) was used to analyze the impedance of the structure

$$e_z \times E_i(x,y) = e_z \times \iint [G^E(x,y|x',y')] \cdot J_S(x',y')\, da' + e_z \times J_S(x,y) Z_S. \quad (1)$$

As the conductive layer is thin compared to an electrical wavelength the surface current $\boldsymbol{J}_S$ has no z-component. Equation (1) is valid only at the surface of a conductor resulting in no z-component of the incidental electrical field $\boldsymbol{E}_i$. The EFIE belongs to the integral equation techniques that match the surface current distribution $\boldsymbol{J}_S$ to a field distribution $\boldsymbol{E}_i$ fulfilling the boundary conditions by means of dyadic Green's functions $[\boldsymbol{G}^E]$ in the space domain. In the space domain (1) is transformed to

$$\vec{E}_i(\vec{x}) = \frac{1}{4\pi^2} \int^{\infty} \int_{-\infty} \left([\tilde{G}^E(k_x,k_y,z)] + Z_S \right) \cdot \tilde{\vec{J}}_S(k_x,k_y) e^{-j(k_x x + k_y y)}\, dk_x\, dk_y. \quad (2)$$

In this analysis, in addition to all the relevant wave phenomena such as dielectric and ohmic losses, radiation, and surface waves, the finite extent of the slot resonator's surrounding metallization has been included.

The method of moments (MoM) is applied to convert the integral equation into a matrix algebraic equation using the subsectional basis function approach. Uniform rooftop-type basis functions

$$B_x(x,y) = \frac{1}{W^2}\left(1 - \frac{|x|}{W}\right) \begin{cases} |x| < & W \\ |y| < & W/2 \\ \text{else} & 0 \end{cases} \quad (3)$$

are defined above equivalent spaced subdomains for the current distributions in x- and y-direction

$$\tilde{J}_x(k_x,k_y) = \sum_{n=1}^{N} A_{xn} \tilde{J}_{xn}(k_x,k_y)$$
$$\tilde{J}_y(k_x,k_y) = \sum_{m=1}^{M} A_{ym} \tilde{J}_{ym}(k_x,k_y). \quad (4)$$

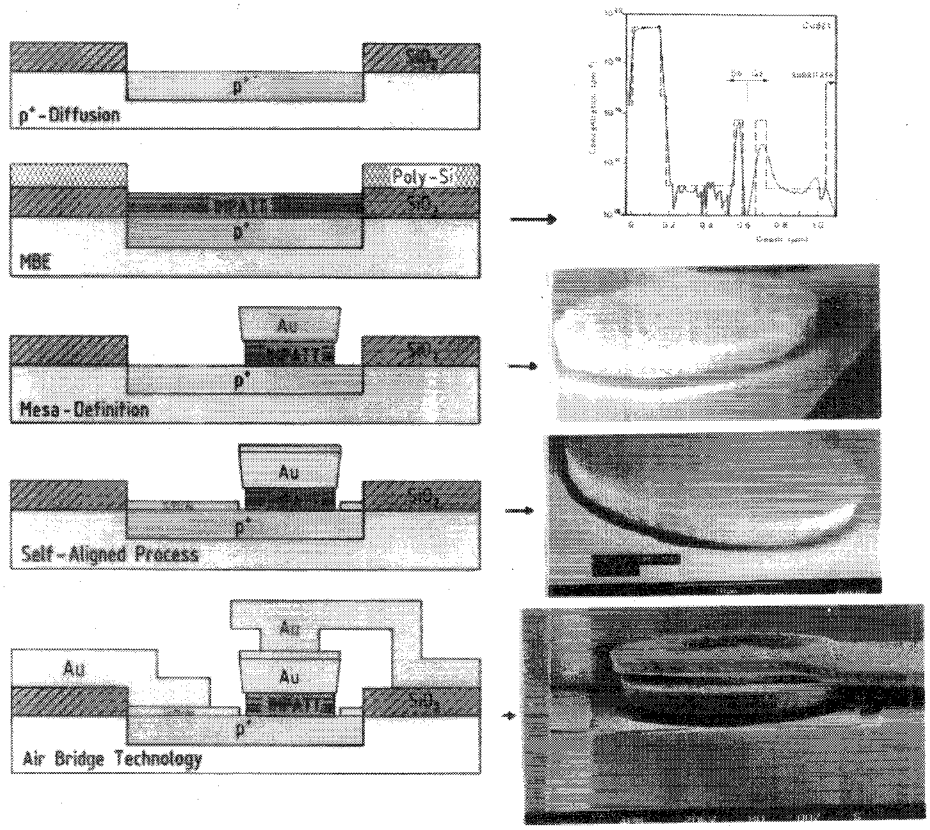

Fig. 6. Fabrication process of the monolithically integrated IMPATT diodes.

Using Galerkin's method the test functions for the MoM procedure are of the same type as the basis functions. We have chosen for excitation a y-directed voltage gap located at the position of the IMPATT diode. Thus the elements of the excitation vector are zero except the one corresponding to the location of the diode. The resulting complex system matrix is partitioned into submatrices of appropriate size. This set of submatrices is then solved by straightforward application of the Gauß algorithm for block matrices [6].

The current distribution has been discretized using 5841 roof-top basis functions. The impedance of the resonator $Z_R = \boldsymbol{R}_R + \boldsymbol{X}_R$ seen by the IMPATT diode versus frequency is shown in Fig. 2. This impedance is derived by evaluating

$$I(x_0, y_0) = \iint \sum_{n=1}^{N} \sum_{m=1}^{M} A_{xn} J_{xn}(x, y) A_{ym} J_{ym}(x, y)\, dx\, dy$$

$$U(x_0, y_0) = \iint E(x, y)\, dx\, dy = U_0$$

$$Z_i = \frac{U_0}{I(x_0, y_0)}. \tag{5}$$

Between 75 and 80 GHz the resistance $\boldsymbol{R}_R$ is below 5 Ω and the reactance $\boldsymbol{X}_R$ is almost linearly increasing with frequency. Similar behavior is observed with simple slot resonators in an infinite metallization plane on ungrounded substrates [4]. However, on thin grounded substrates the resistance of these slot resonators is higher than 30 Ω due to the excitation of the parallel plate waveguide mode [5]. Obviously, the low resistance is caused by additional patch resonances. This is confirmed by the calculated current distribution shown in Figs. 3 and 4. Fig. 3 depicts the absolute value of the vector sum of $\boldsymbol{J}_{Sx}$ and $\boldsymbol{J}_{Sy}$. The direction of the surface current $\boldsymbol{J}_S$ in each subdomain is presented graphically in Fig. 4. Only half of the structure is shown due to its symmetry.

A higher order patch resonance is excited by the slot resonator resulting in a high current through the diode, i.e. a low resistance is seen by the diode. At the operation frequency the conditions $R_R + R_D = 0$, $X_R + X_D = 0$ have to be fulfilled, where the diode resistance $\boldsymbol{R}_D$ and the diode reactance $\boldsymbol{X}_D$ are functions of the diameter $2\boldsymbol{r}$ of the diode, of the current density $\boldsymbol{J}$, and of the modulation depth $\boldsymbol{m}$. Knowing the frequency dependence of the resonator impedance and the parameters of the actual diode the operation frequency can be calculated [7]. Matching the real and the imaginary part of the diode impedance to the resonator impedance separately, the points of intersection of the resulting curves give the oscillation frequency. Fig. 5 shows the calculated curves for diodes with 7 and 9 μm radius. These curves are achieved by varying the modulation depth assuming a maximum temperature rise at the junction of 200 K which determines the current density. The points of intersection are at frequencies around 74 and 75 GHz for the 7 μm and 9 μm diode, respectively.

III. Fabrication Technology

Integrated transmitters based on the layout shown in Fig. 1 have been realized. A SIMMWIC (silicon millimeter wave

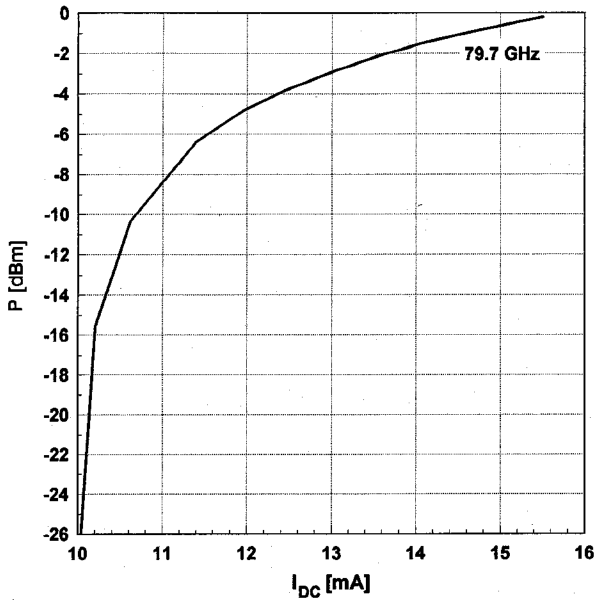

Fig. 7. Measured CW radiated power versus bias current.

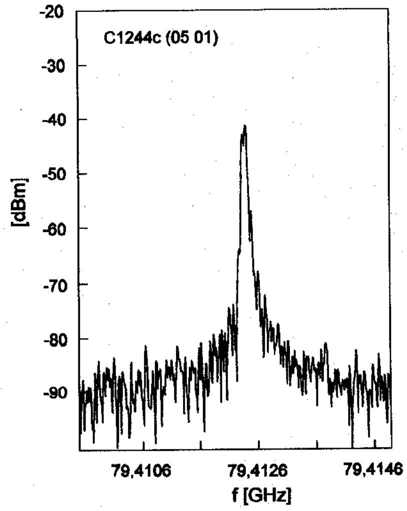

Fig. 8. Spectrum of the radiated signal.

integrated circuit) fabrication process with a self stopping etchant, self aligned contacts, silicon nitride passivation and air-bridge technology has been used. The fabrication process is schematically shown in Fig. 6.

First, the high resistive (ϱ>4000 Wcm) 4-in. silicon substrates are thermally oxidized and highly doped p^+-layers are formed by B-diffusion. A sheet resistance smaller than 2.5 Ω/□ and a surface concentration greater than 10^{20} cm^{-3} is achieved (see Fig. 6). Next, the active layers of sophisticated IMPATT profiles are grown by Si-MBE (see Fig. 6). The growth temperature is 550°C. Then the top contact of the IMPATT diode is defined and the diode is mesa etched in a self stopping etchant (aqueous KOH solution). A slight undercut is performed. This undercut enables self aligned technology for defining the lower contact and reduces series resistance. To reduce surface leakage currents the mesa edges are passivated by a 150 nm thick, low temperature (300°C) plasma-enhanced deposited Si_3N_4 film. Finally, air bridge technology is applied for forming the top contact of the diode.

IV. Experimental Results

In Figs. 7 and 8 the measured radiated power and spectrum in CW mode are shown, respectively. A maximum power of 1 mW at 79.7 GHz has been achieved with an excellent carrier-to-noise ratio of 81.7 dBc/Hz at an offset of 100 kHz. The deviation of the measured from the theoretically predicted values of frequency and power is -5.9% and -1.5 dB, respectively.

V. Conclusion

Monolithic integrated transmitters on thin grounded silicon substrates for automotive applications in the millimeter wave range have been investigated theoretically and experimentally. As a resonant structure a patch resonator fed by a slot resonator has been used, which meets the impedance requirements of IMPATT diodes even on thin grounded substrates. This resonator concept is compatible to monolithic integration and allows a simple and efficient application of the heat sink. The transmitter element occupies a substrate area of only 6 mm^2. The transmitter elements deliver a radiated power of up to 1 mW at 80 GHz with an excellent carrier-to-noise ratio of 81.7 dBc/Hz at an offset of 100 kHz.

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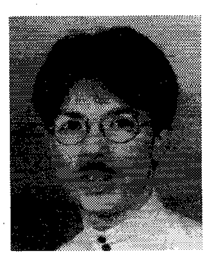

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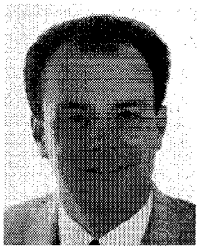

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J.-F. Luy (M'86), for a photograph and biography, please see p. 713 of the April issue of this TRANSACTIONS.

Karl M. Strohm, for a photograph and biography, please see p. 713 of the April issue of this TRANSACTIONS.

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