deformed $E$-plane, which confirms the effect of transverse currents on the $E$-plane rather than on the $H$-plane.

## V. Conclusion

With the examples provided here it has been shown that dual-band elements can be designed for use on monolithic GaAs active antennas, with planar configurations offering improved characteristics compared to stacked elements. The alliance of monolithic device technology and printed-circuit antennas has opened an unlimited number of possibilities for both antenna and system designer. Technology has been developed for 90 GHz systems, but higher operating frequencies for new communication systems are coming fast, and research is even moving toward the 1 THz region [10]. Likewise, new materials such as InP will play an important role. A combination of different permittivities on the same substrate, say, small islands of high dielectric constant material on a low dielectric constant substrate could be an important option to overcome the diverse problems encountered when trying to integrate microstrip antennas with acvtive circuits.

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# Planar Millimeter-Wave Antennas Using $SiN_x$-Membranes on GaAs

M. Stotz, G. Gottwald, H. Haspeklo, and J. Wenger

*Abstract*—**Planar aperture coupled microstrip antennas for 77 GHz are demonstrated for the first time. As far as possible standard GaAs monolithic microwave/millimeter-wave integrated circuit (MMIC) technology is used to realize the antennas. The antenna patches are suspended on a thin dielectric $SiN_x$ membrane on GaAs substrate. Therefore a novel plasma-enhanced chemical vapor deposition (PECVD) process step for the fabrication of the membranes is developed and described. The single antenna patches are coupled to a microstrip line through an aperture in the ground metallization. The method of moments in spectral domain is applied to design the patches. The feed network of a 3 × 1 antenna array for homogeneous excitation is simulated and optimized with a microwave design system (MDS). From reflection measurements the operation frequency of this triple patch antenna is determined to be 77.6 GHz. The farfield antenna characteristics are measured in an anechoic chamber, showing good agreement between simulated and measured results and a co- to cross-polarization isolation better than 30 dB.**

## I. Introduction

Over a period of more than 25 years the development of microstrip and aperture coupled patch antennas has emerged as a major activity within the antenna field. The interest in these antenna types lies in their advantages such as low cost, mass production, lightweight, conformity to surface, and dual polarization capability. Especially at millimeter-wave frequencies the occupied area on the substrate becomes small enough, so that it can directly be integrated with microwave integrated circuits. When using semiconductor materials (Si or GaAs) as dielectric substrates for antennas the relatively high permittivity ($\varepsilon_r \approx 12 \cdots 13$) is disadvantageous due to the reduced radiation efficiency. Therefore technological measures have to be taken to reduce the effective $\varepsilon_r$ to reasonable low values. One means is, to etch many closely spaced via-holes under the antenna patch or to reduce the thickness of the substrate locally under the patches to obtain a decreased $\varepsilon_r$ [1], [2]. Another possibility is the use of thin membranes fabricated on Si or GaAs by using $SiO_2$ and/or $SiN_x$. On Si substrates this technique has been intensively used in [3]–[6] for the fabrication of antennas, detectors, and filters for frequencies well up into the submillimeter-wave range.

This communication describes a novel approach to realize planar antennas for automotive radar sensors for 77 GHz (e.g., autonomous intelligent cruise control, collision avoidance, or road surface detection). The realization of 3 × 1 antenna arrays suspended on thin, large, and stable $SiN_x$ membranes on GaAs substrate is reported for the first time. In the following the design steps of the aperture coupled patches, the process procedures for the fabrication of the membranes compatible with the MMIC technology, as well as the measured performance of the antenna array are described.

## II. Design

For the radiating element the aperture coupling antenna concept is chosen (Fig. 1). Despite the necessity of multilayer fabrication

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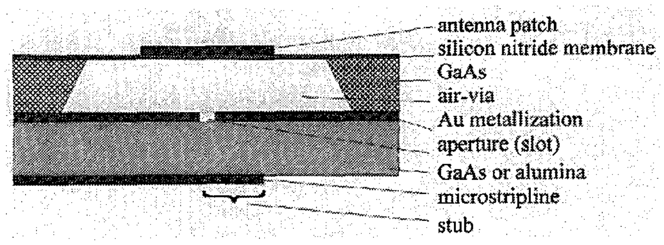


Fig. 1. Schematic cross section of a microstrip aperture coupled antenna patch suspended on a thin $SiN_x$ membrane.

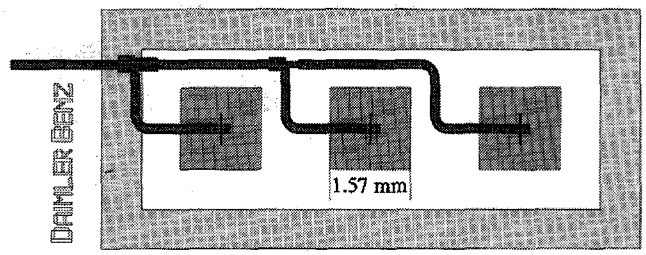


Fig. 2. Layout layers of an aperture coupled 3 × 1 patch antenna array.

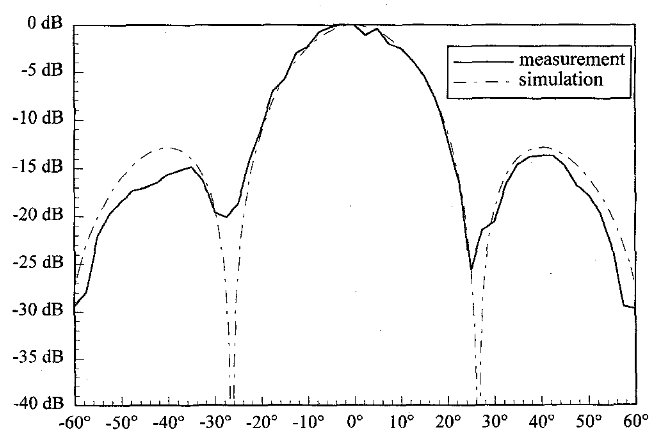


Fig. 3. Simulated and measured far field radiation patterns (E-plane) of an aperture coupled 3 × 1 patch antenna array.

steps, it has several advantages compared to conventional microstrip antennas: An independent choice of substrate materials and separate optimization of feed network and radiating element is possible, spurious radiation from the feeding circuit is suppressed, and via connections are not necessary. The design of the single aperture coupled patch element involves the following steps: First the dimensions of the antenna patch are determined by a cavity model [7] to be resonant at the operation frequency of 77 GHz. The side length of the squared patch is found to be 1570 $\mu$m. The width of the aperture (slot) is chosen to be 50 $\mu$m. On the one hand it has to be large enough to enable good electromagnetic coupling through the slot, on the other hand it has to be small enough to be modeled as a lumped series impedance in the equivalent circuit and to apply the reciprocity theorem for the input reflection coefficient [8]. To determine the length of the aperture the whole element structure is analyzed by the method of moments in spectral domain [9] which assumes infinite homogeneous substrate. While the silicon nitride membrane and the substrates for the microstrip line are well defined, the air-via in the GaAs substrate however has to be modeled as a homogeneous layer for which an effective permittivity of $\varepsilon_{r,\text{eff}} = 1.05$ results. Four sinusoidal modes are used to model the current distribution on the patch, one piecewise sinusoidal mode is assumed in the slot and the microstrip line is described by incident and reflected quasi-TEM waves. The slot length is found to be 597 $\mu$m to yield an input resistance of 50 $\Omega$. The imaginary part (reactance) is compensated by the open stub of the microstrip line. With the calculated reflection coefficients a series-parallel feed network for a triple patch antenna with homogenous excitation is designed and optimized by using the microwave design system (MDS) from Hewlett Packard. The different layers of the final design are depicted in Fig. 2 as a transparent view.

## III. Fabrication

For the fabrication of thin mechanically stable membranes on GaAs substrate new process steps are developed. The $SiN_x$ layers are deposited in a parallel plate plasma-enhanced chemical vapor deposition (PECVD) system using $SiH_4$ and $NH_3$ at 300°C. A 2 $\mu$m layer thickness is suitable to support the patch metallization. The stress in the $SiN_x$ layer is reduced by using multiplex RF frequency deposition [10]. PECVD of $SiN_x$ with an RF stimulation above 4 MHz usually results in a tensile stress in the layer, a lower RF frequency in compressive stress [11]. Standard frequencies of 13.56 MHz and 186 kHz are used. By precise adjustment of the alternating periods for high and low RF frequency deposition layers with small residual stress down to about $4 \times 10^7$ Pa tension and $-3 \times 10^7$ Pa compression are realized.

After the deposition of the $SiN_x$ layer optical lithography is used to define the patches and microstrip lines. TiW/Au is sputtered as a starting metallization followed by a 3-$\mu$m-thick electroplated Au layer. In the following the 625-$\mu$m-thick GaAs wafers are thinned down to 150 $\mu$m. Afterwards the GaAs below the patches is removed by using a wet chemical etch solution of $H_2SO_4$:$H_2O_2$ = 1:4. In Fig. 1 a schematic cross section of a microstrip aperture coupled antenna patch suspended on a thin $SiN_x$ membrane is pointed out.

By using the developed technology, freestanding $SiN_x$ membranes up to a size of $4.6 \times 4.6$ mm$^2$ and $3.2 \times 8.8$ mm$^2$ are realized on GaAs wafers, respectively. The thermal stability of the membranes is tested over a wide temperature range from 77 K up to 400 K. Layers with tensile stress are destroyed when cooled down to 77 K, while membrane antennas under small residual compressive stress withstand temperature cycles between 77 K and 400 K without any problems. Neither layer type shows any degradation within a temperature range from 228 K to 373 K, specified for many electronic applications (e.g., automotive systems).

## IV. Measurements and Results

For the RF characterization of the antennas a transition from waveguide to microstrip is designed and fabricated, which covers the whole E-band from 60 GHz to 90 GHz. The microstrip line of the transition is connected to the microstrip transmission line of the antenna by bond ribbons. The membrane antennas are fixed onto the backside of the microstrip substrate by glueing.

For the measurement of the return loss $S_{11}$ a HP8510C vector network analyzer with a HP85105A millimeter-wave controller for extended V-band operation (50 GHz to 80 GHz) is used. The resonant frequency of an aperture coupled triple patch antenna is determined to be 77.6 GHz. The measured input reflection coefficient at that frequency is −44 dB.

The farfield antenna pattern has been measured in an anechoic chamber. The antenna under test is used as the transmitting antenna. Two corrugated horn antennas with vertical and horizontal polarization are mounted as receiver antennas at 3 m distance. Fig. 3 shows the measured E-plane radiation pattern of the triple patch antenna at 77.6 GHz. The zero degree value is determined by adjusting the antenna for maximum radiated power (0 dB value). The antenna shows very symmetrical patterns. The 3 dB and 10 dB mainbeam widths are 22° and 38°, respectively. The maxima of the sidelobes are −14 dB at ±40°. Measured and simulated data (dash-dotted line in Fig. 3, [12]) show very good agreement. The measurement is limited to ±60° due to the measurement setup. The cross-polarization isolation of the triple patch antenna is better than −30 dB at 0°.

## V. Conclusion

Planar microstrip antennas for operation for 77 GHz have been realized and tested. For the fabrication of the antennas new technology steps have been developed which are compatible to standard GaAs processing techniques. The antenna patches are suspended on thin freestanding $SiN_x$ membranes on GaAs substrate. The patches are coupled through an aperture in the ground metallization of the feeding microstrip circuit. For the design the method of moments in spectral domain has been applied. The triple patch antennas exhibit symmetrical radiation patterns with a 10 dB mainbeam width of 38°. Very good correspondence between measurement and simulation has been observed. To the authors knowledge the demonstrated results represent the first data for aperture-coupled millimeter-wave patch antennas on thin membranes fabricated on GaAs.

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# Application of the Spatial Finite-Difference and Temporal Differential (SFDTD) Formulation to Cylindrical Structure Problems

Alan Ming Keung Chan and Zhizhang Chen

*Abstract*—**The recently developed spatial finite-difference and temporal differential (SFDTD) approach is extended to dielectric loaded cylindrical environments. Although the method is developed differently, its resultant formulation can be directly obtained from the corresponding finite-difference time-domain (FD-TD) method. Good agreements between the SFDTD and reference results are obtained for different configurations of dielectric loaded cylindrical structures. As a result, the SFDTD approach is shown to be generally effective and robust for resonant structures.**

## I. Introduction

Cylindrical cavities, especially in dielectric-loaded structures, have been widely used in many microwave applications such as filter, oscillator, and dielectric measurement [1]–[4]. Characterization of these structures for applications in microwave circuits is required. Different approaches for the structures consisting of transmission media and their boundaries have been used. In the past, analytical methods, such as spectral domain method and mode matching technique, were applied; however, the methods require the specific structures and cannot be applied to the problems with arbitrary geometry. Furthermore, the realistic features such as finite metallization thickness, mounting groove, and irregularities caused during manufacturing, cannot be easily accounted for. Therefore, very accurate characterization numerical techniques are essential to model the problems.

Numerical techniques such as the finite element method (FEM), the method of moment (MoM), the boundary element method (BEM) have evolved in the last two decades. Recent advances in modeling concepts and computer technology have expanded the scope, accuracy and speed of these methods. Typically, time-domain techniques such as the finite-difference time-domain (FD-TD) method and the transmission line matrix (TLM) method have received growing attention due to the simplicity and flexibility of their algorithms. Programs based on these techniques can be applied to solve problems with structures that the analytical approaches cannot deal with. However, when these time-domain methods are applied to resonant structures, they encounter certain difficulties. For example, for a high-Q structure, long iteration may be required. Also, resonant modes may be missed due to the placement of excitation or output points at the null field points of the modes.

Recently, a numerical method which circumvents the problems mentioned above is developed and applied to homogeneous rectangu-

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