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In-Situ Probes for Antenna Array Calibration

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***Abstract*— A novel calibration network for patch antennas is proposed. We introduce magnetically coupled in-situ probes, which excite the fundamental patch mode. In that way, finite array effects and mutual coupling can be detected, providing the opportunity for online calibration. The specific advantages of the approach are demonstrated for linearly polarized patch antennas. Measurement results of a single patch with the integrated probes agree with simulation. A two by two antenna array with in-situ probes is simulated to demonstrate the calibration accuracy in theory.**

I. INTRODUCTION

Electronically steerable antenna arrays are very attractive for mobility scenarios in future broadband satellite communication systems [1]. Patch antennas are commonly used in such antenna arrays. The calibration of these antenna elements is an important task with regard to the overall antenna performance, such as gain, side lobe level or pointing accuracy [2].

Generally, one can distinguish between two calibration concepts – the external and the internal one. The former one is the best known approach and yields the most accurate results with plane wave excitation at bore sight, since, in general, this reproduces the normal operation condition of an array [3]. However, for obvious reasons, this concept may not always be practical for mobile users, at least in the transmit case. Indeed, as calibration parameters may vary in time due to environmental effects, a necessary recalibration becomes difficult with the far-field method. For these reasons, an autonomous calibration system with online monitoring capability is desirable. The monitoring solution should be adaptable to any array size.

In that respect, the internal calibration is more convenient for mobile user scenarios. According to [3] the internal calibration for a receiving antenna is normally carried out by injecting a calibration signal behind each antenna element. Commonly, this is achieved by means of a coupler, as it has been demonstrated in the patch antenna array design in [4]. In that way, only hardware chains are calibrated. Since this approach does not take into account the mutual coupling of radiating elements and finite array effects, the calibration possibility is limited compared to the far-field approach [3].

The in-situ probes proposed in this contribution (see Fig. 1) combine advantages of both calibration approaches – monitoring possibility of the internal probes and calibration accuracy of the far-field method. These probes are placed inside the cavity of a patch antenna. The fundamental mode of the patch is excited by the magnetically coupled probes, thus approximating the far-field situation. The fundamental mode excitation allows for amplitude and phase error detection of both the radiating elements and the connected (active) circuitry.

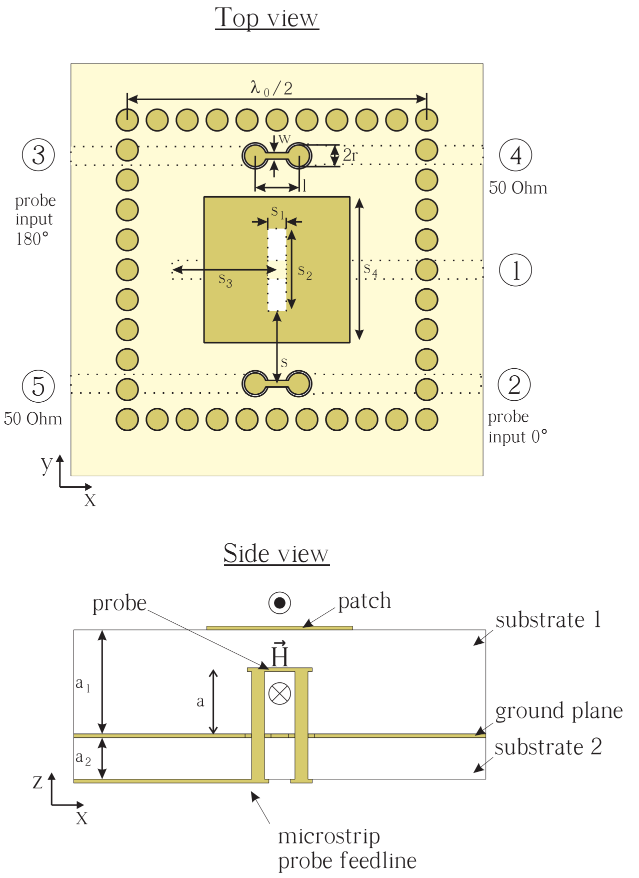

Fig. 1. Schematic of the magnetically coupled in-situ probes operating at 20 GHz. Parameter values: s=1.50 mm, s_1=0.45 mm, s_2=2.30 mm, s_3=2.32 mm, s_4=3.30 mm, l=1.00 mm, w=0.15 mm, r=0.30 mm, λ_0=15.00 mm, a=0.30 mm, a_1=0.50 mm and a_2=0.20 mm.

II. CALIBRATION PROBES

A. Approach

The in-situ probes to be proposed in this work should have the ability to detect mutual coupling and finite array effects. To this end the fundamental patch mode has to be excited by the probes since this corresponds to the actual antenna operation. Ideally, no additional information for the calibration is needed.

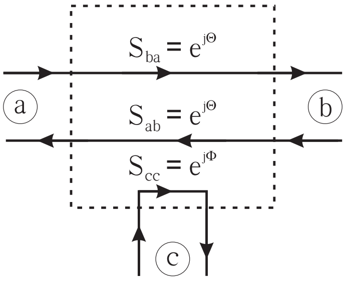

Fig. 2. A three-port network representation of a single-feed probe in combination with a patch antenna.

Another important requirement is the matching of the probe. That means, the approach has to be applicable for both receive and transmit antennas. For instance, the calibration network of the receiving antenna studied in this work has an active transmit path for which strong reflections have to be avoided. It is well known that a lossless and reciprocal three-port network cannot be matched at all ports simultaneously [5]. This context is clarified in Fig. 2. The antenna feed port is denoted as (a), the radiating patch (port toward free space EM waves) as (b), and the probe as (c). That is, a lossless one-port probe in combination with the perfectly matched patch antenna (two-port network) cannot be matched, at all.

This matching problem can be avoided by utilizing a two-port probe, with one port being terminated by 50 Ω. The corresponding schematic of the proposed probes integrated inside the cavity of the patch is shown in Fig. 1. The resulting four-port device can be described as a coupler, in which the magnetic coupling can be adjusted by changing the distance s between the coupled line of the probe and the slot of the antenna feed line. In Fig. 3 the frequency response of the coupling strength c_{21} (power flow from the probe to the feed line of the patch) for various values of s is shown. This dependence can be used for adjusting a predefined signal level, for instance to comply with power limitations of the calibration circuitry. Because of reciprocity the coupling c_{21} defines at the same time the additional signal loss due to the probes in normal operation mode of the patch.

In order to maintain radiation symmetry two probes have to be arranged in parallel. The electrical length of the coupler amounts to 180°. This can be explained by the description of the radiating element as a piece of transmission line having an electric length of 180° [5]. Thus, the two probes have to be excited with opposite phase (ports two and three in Fig. 1). The relation between the radiation symmetry and the port excitation of the probe is demonstrated in Fig. 4. Four relevant combinations are examined. Port numbers are defined in Fig. 1. Ports two and three appear as the proper choice as is verified by these radiation results. Only with an opposite phase excitation of the two parallel probes a symmetrical radiation can be obtained. As a result, only the desired fundamental patch mode radiates notably. This radiation emulates the patch radiation in normal operation mode when excited by the microstrip feed. Hence, mutual coupling and finite array effects are essentially taken into account.

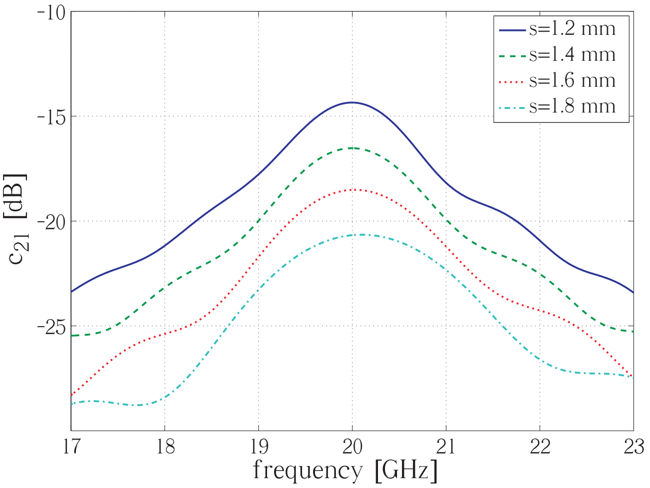

Fig. 3. Variation of coupling strength c_{21} as function of frequency.

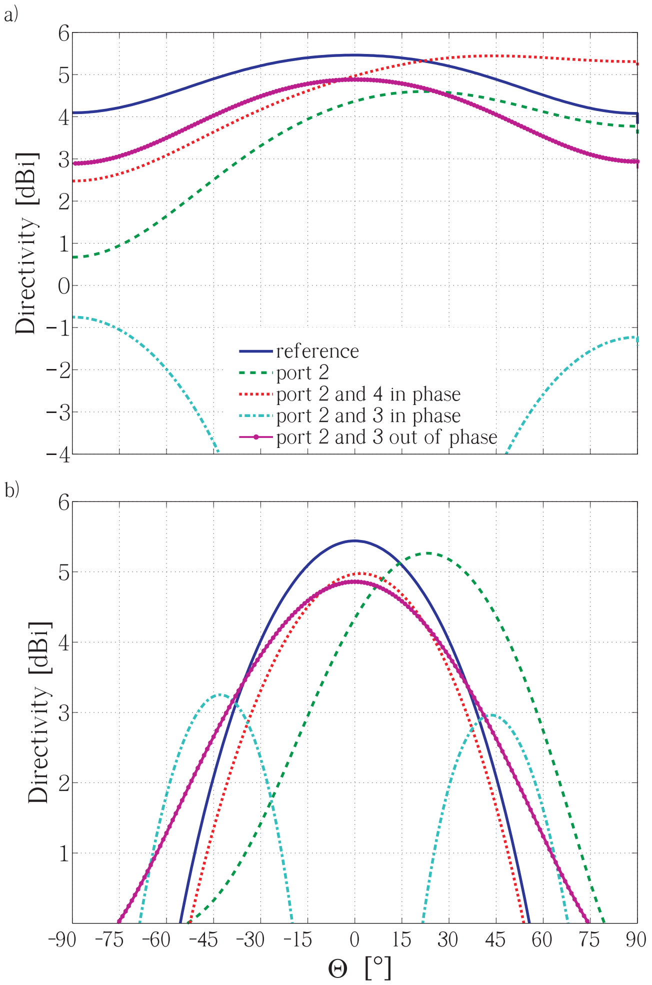

Fig. 4. Directivity of the patch excited by different port combinations as function of Θ in a) the x-z-plane (E-plane) and b) the y-z-plane (H-plane).

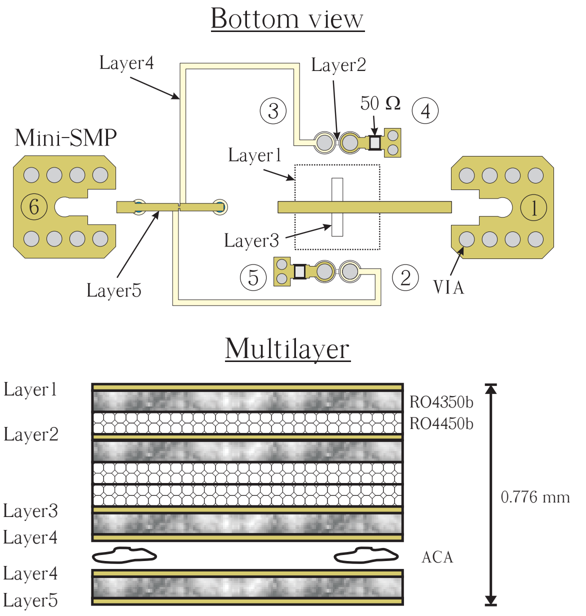

Fig. 5. Schematic of the in-situ probes with integrated Marchand balun (top) and the corresponding multilayer stack (bottom). For parameter values of the patch and probe see Fig. 1

B. Multilayer Design at 20 GHz

The schematic of the in-situ probes from Fig. 1 has been completed by an additional balun, as shown in Fig. 5. A Marchand balun [6] is employed to excite the probe ports with opposite phase and equal amplitude as required for a symmetric radiation pattern. In order to maintain the matching condition of the probes, the unused ports have to be terminated by 50 Ω resistances. We use RF-resistors in a 0302 SMD package 0302 from IMS [7]. For measurement purposes mini-smp connectors are mounted.

The circuit in Fig. 5 provides radiation symmetry and good matching but is not scalable. This is because the test structure occupies more area than available in antenna arrays with half free space wavelength element spacing. For a proof of concept, however, a demonstrator with as few layers as possible is considered. This is to keep the multilayer stack realizable with our fabrication process. In a full scale antenna, the additional balun structure presented here is to be integrated in additional layers beneath the antenna which is no problem in standard industrial processes. As a consequence of these limitations the corresponding multilayer stack is realized as two separated units being bonded with an anisotropic conductive adhesive (ACA) as indicated in Fig. 5. Otherwise a substrate layer thickness of 50 μm is required to fabricate the proposed design within standard multilayer processes.

The balun is realized as a broadside coupler, i.e. it emulates broadside radiation of the antenna array. This simplifies the quantitative coupler design. The arrangement of the balun along with the design parameters is shown in Fig. 6. The signal at port one is equally distributed between ports two and three, exciting the probes with opposite phase and equal amplitude. Simulation of the Marchand balun with CST Microwave Studio [8] shows matching of better than 11 dB and phase and amplitude imbalance of 3 ^{0} and 0.05 dB, respectively. The obtained phase imbalance is equalized by the feeding lines on layer 4 which have slightly different electrical length. As a result the ideal symmetrical probe excitation will only be affected by the amplitude imbalance of 0.05 dB. This amplitude error is negligibly small.

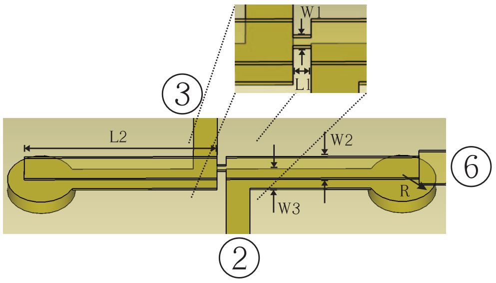

Fig. 6. Enlarged schematic of the integrated Marchand balun. Parameter values: R=0.3 mm, L_1=0.8 mm, L_2=1.7 mm, w_1=0.07 mm, w_2=0.28 mm, w_3=0.25 mm.

The multilayer design of a single radiation element with the in-situ probes and the integrated balun has been realized and measured. Matching of the antenna and the probes as well as the coupling c_{21} are shown in Fig. 7. For comparison the simulation results are included, too. The effect of the mini-smp connectors is eliminated by a TRL calibration. Thus, comparison between simulation and measurement is conducted at the same reference plane. Satisfactory agreement between the simulation and measurement results can be stated. The behavior of the measured coupling c_{21} is similar to the simulated one. The simulated matching condition of the patch which represents an important parameter is reproduced in practice. Negligibly small shift in the resonance frequency is observed. This frequency shift can be attributed to fabrication tolerances.

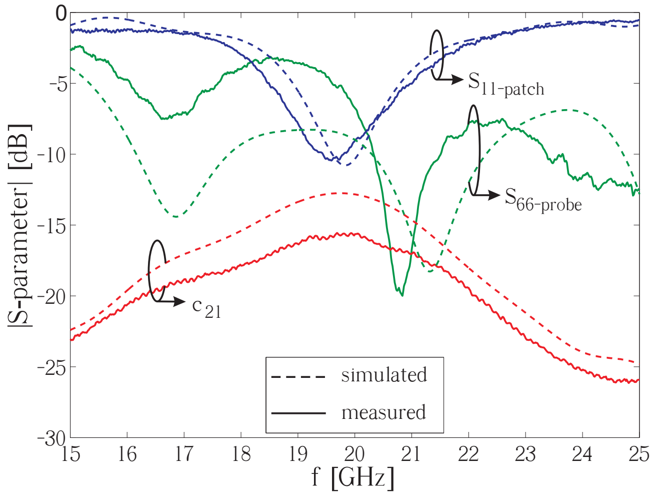

Fig. 7. Measured (solid lines) and simulated (dashed lines) S - parameters of the antenna element from Fig. 5.

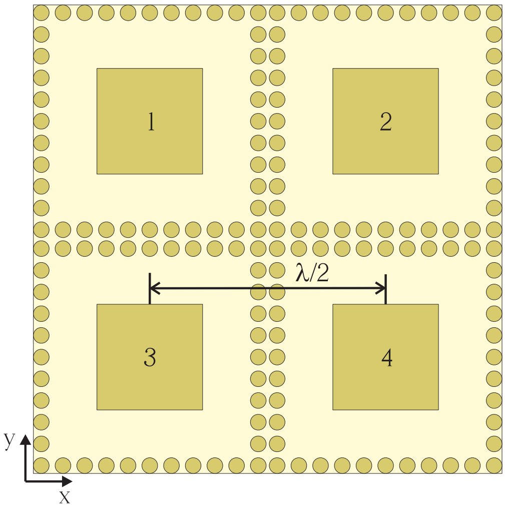

Fig. 8. Arrangement of the investigated 2 x 2 antenna array with integrated in-situ probes.

III. CALIBRATION OF A 2 X 2 ARRAY

To demonstrate the potential of the proposed in-situ calibration probes a 2x2 array is investigated here by means of a CST simulation. The antenna elements are numbered as depicted in Fig. 8. The received amplitude and phase at the antenna ports for probe excitation is compared to the amplitude and phase for plane wave incidence at bore sight – the normal operating mode. All probes are simultaneously excited with equal amplitude and phase to emulate the plane wave scenario. Thus, a close match of both simulation results is expected.

The resulting amplitude and phase distributions of the antenna elements are shown in Fig. 9. The amplitudes and phase angles of antennas 2, 3, and 4 are related to antenna 1, taken as reference element in the array. In this way, variations of the received signal levels caused by differences in the excitations are compensated. The amplitudes and phase angles of the calibration scheme using (ideal) couplers placed outside the antenna cavity are included in Fig. 9 as well. As such a coupler does not excite the patch itself the antenna imperfections are not taken into account. Therefore, the amplitudes and phases of all patches are equal, here.

Despite small residual errors the relative phases of the elements excited by the plane wave are reproduced by the excitation through the in-situ probes. The relative magnitudes resulting from plane wave and probe excitation exhibit an inverse slope. Analysis of antenna arrays with different sizes have been conducted, showing the same inverse magnitude response. That is, this effect can be used as a general calibration rule. The precisely reproduced behavior of the antenna elements' phases and magnitudes indicates the potential of the in-situ probes. The observed coincidence between plane wave and probe excitation demonstrates the ability of the probes to emulate mutual coupling and finite array effects.

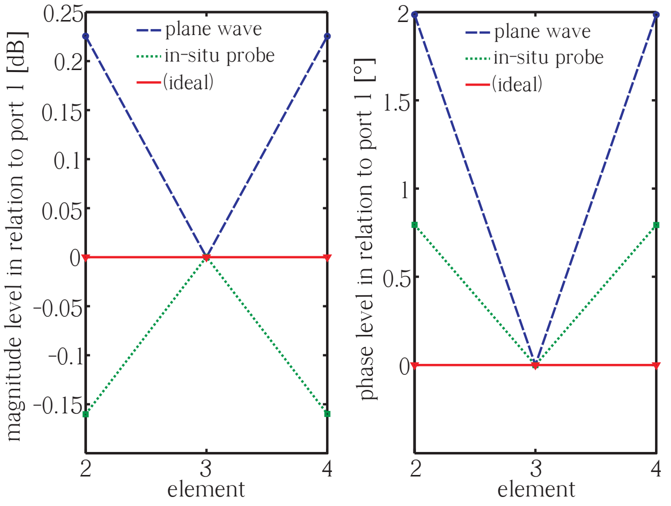

Fig. 9. Detected amplitudes and phases of the 2 x 2 array from Fig. 8 (antenna one is the reference element).

IV. CONCLUSION

In-situ calibration probes are presented in this work. These probes are integrated in the cavity of a patch antenna. They account for the detection of errors caused by finite array effects and mutual coupling. Measurement results of a single antenna element equipped with the probes are in agreement with simulation. The potential of the in-situ probes is demonstrated by means of a simulation of a 2 x 2 antenna array.

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