Highly sensitive optoelectronic E-field probes for interference free near field antenna measurements

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Abstract

The paper presents an E-field probe in particular for near field measurements. Its extremely small size of 5×5×5mm³ and the optical power supply and optical signal transmission ensures a negligible field distortion.
Unlike field probes using rectifying diodes, the probe system presented here preserves the full spectral information of the field. It enables measurements both in the time and frequency domain. For CW signals the magnitude as well as the phase of the sinusoidal field strength can be determined. A sensitivity of 50µV/m/√Hz has been demonstrated.
The probe was used for near-field measurements of a patch antenna array at a frequency of 2GHz. The results have been used to determine an equivalent magnetic current source distribution of the antenna array.

1 Introduction

Over the last years several miniaturized E-field probes have been presented [1,2,3,4,5,6,7]. They are needed for (antenna) near field measurements, but also for assessments of the specific absorption rate (SAR) and other EMC related topics. While for SAR and many EMC measurements it is often enough to determine the magnitude, for antenna near field investigations it is necessary to know both the amplitude and the phase (vector measurement). For modulated signals a field probe capable of time domain measurements is desired.
A new approach for the measurement of broadband signals or field strengths, respectively, is an opto-electronic probe based on an optical signal transmission and a vertical cavity surface emitting laser (VCSEL) as transmitter element [5]. Due to the low threshold currents of VCSELs an optical power supply can be used in order to minimize both the physical probe dimensions and the field perturbations induced by the probe connection line.
The initial probe principle has several disadvantages, primarily the high-pass filter characteristic. This makes the probe unsuitable for time domain measurements. The frequency response can be flattened by the integration of a FET based preamplifier. Furthermore the preamplifier improves the sensitivity by orders of magnitudes.
The first part of the paper (section 2-4) describes the field probe system, the theory as well as the probe construction and its characteristic. The second part (section 5,6) presents near-field measurements of a patch antenna array using this probe.

2 Probe principle and construction

The probe system consists of the field probe itself and the remote unit (fig. 1). The latter one contains the optical power supply system and the opto-electronic converter (optical receiver). The field probe has a size of 5×5×5mm³. It mainly consists of the dipole electrodes, an HEMT based impedance transformer (source follower), a solar cell array and the laser diode (VCSEL) for the signal transmission to the remote unit. The probe and the remote unit are connected by a fiber bundle for the optical power supply and a single optical fiber for the signal transmission.

Figure 1: Principle of the probe system

Within the remote unit the light of a high power laser diode is launched into the fiber bundle which leads the light to the solar cell array in the probe. For an optical input power of ≈50mW the solar cells give an output voltage of 4.5V at a current of 2.3mA. This current is used for biasing the VCSEL.
An RF E-field surrounding the probe gives a corresponding RF voltage across the dipole electrodes. The electrodes have a size of $5 \times 5 \text{mm}^2$. This voltage is transferred to the VCSEL by means of the HEMT and modulates the VCSEL current. Both the VCSEL and the HEMT can be used for frequencies up to several GHz. The output light of the VCSEL is launched into an optical fiber and transmitted to the remote unit. There a photo diode and a transimpedance amplifier (TIA) convert the optical signal into an electrical one (output signal of the probe system). This output signal corresponds with one spatial component of the electric field strength with several GHz bandwidth. Thus for CW signals the output signal contains the information of both magnitude and phase of the sinusoidal E-field.

A completely assembled probe is shown in fig. 2. The fiber bundle with the black sheathing is that for the optical power supply while the smaller green covered fiber is the signal fiber. Within the field probe the solar cell array as well as all other components (HEMT, resistors, VCSEL) are mounted on a standard microwave substrate.

![E-field probe](image)

**Figure 2**: Assembled field probe

### 3 Probe theory

For regular operation the HEMT needs a negative gate bias voltage. This is generated by a voltage divider: $R_1$ (22kΩ) and $R_2$ (68kΩ). The circuit topology ensures a sufficient stabilization of this gate-source voltage against variations of the supply voltage.

The resistors $R_1$, $R_2$ and the gate capacitance act as a high pass filter. I.e. even these probes with an integrated FET preamplifier will exhibit an high pass filter characteristic. However, due to the much higher resistance of $R_1$, $R_2$ compared to that of the VCSEL itself the lower 3dB frequency of the new probe (several MHz) is lower by orders of magnitudes than that of the probe without a preamplifier (many GHz). Thus time domain measurements in the MHz range are feasible.

The upper frequency limit is mainly given the component parameters and the parasitics. The HEMT as well as the VCSEL can be operated up to several GHz.

In order to obtain a simplified equivalent circuit diagram the following assumptions and simplifications are made: The dipole electrodes are small therefore the antenna impedance can be considered as that of a capacitor $C_{ant}$ (approx. 100fF). The HEMT is modeled by the gate source capacitance $C_{GS}$ (0.5..0.6pF) and the transconductance $g$ (30..40mS @ $I_D$=3mA). The output impedance (both resistive and capacitive) of the HEMT and their gate drain capacitance as well as various parasitic capacitors and inductors are neglected. The resulting small signal equivalent circuit is shown in figure 3.

![Small signal equivalent circuit](image)

**Figure 3** Small signal equivalent circuit

$U_{ant}$ is the antenna source voltage, $R_{laser}$ is the differential resistance of the VCSEL (200..300Ω). For the voltage modulating the VCSEL ($U_{laser}$) we get

$$ U_{laser} = U_{ant} \cdot \frac{R_{laser} \cdot (g + j\omega C_{GS})}{1 + \frac{C_{GS}}{C_{ant}} \cdot R_{laser} \cdot (g + j\omega C_{GS})} $$

(1)

For the given parameters $U_{laser}$ is approximately half the antenna source voltage.

The sensitivity of the field probe is determined by this voltage ratio, the electro-optic conversion factors of the VCSEL and the optical receiver and by the noise. When using a VCSEL with a very low relative intensity noise (RIN) the overall noise of the system is determined by the shot noise of the photo current in the optical receiver. The theoretical sensitivity limit for a probe of the given physical dimensions is approximately $5\mu\text{V/m}/\sqrt{\text{Hz}}$ (noise equivalent field strength).

### 4 Measured probe characteristics

Figure 4 shows the measured probe dynamic range at a frequency of 100MHz.

The probe noise is $50\mu\text{V/m}/\sqrt{\text{Hz}}$. Although this value is 20dB away from the theoretical limit it is better than all other E-field probes known so far. At a field strength of 200V/m the 1dB compression point is reached, giving a dynamic range of 132dB (1Hz).
Figure 4: Linearity, noise and dynamic range

Figure 5 shows the frequency response from 0 to 500MHz. The field was generated using a Crawford cell. Due to resonances of the cell we obtain the peak at approx. 400MHz and further ones at higher frequencies. Therefore this equipment allows (calibration) measurements only up to 400MHz.

Figure 5: Frequency response measurement using Crawford cell

The frequency response was measured again using a GTEM cell for frequencies up to 3GHz. The general applicability of the probe could be demonstrated. However according to these measurement data the sensitivity decreases by about 20dB from MHz to 3GHz. This contradiction to the theory is not understood so far. A fault of the GTEM cell cannot be ruled out.

5 Patch antenna near-field measurements

A planar e-field scanner has been set-up using the field probe mounted at a xy-positioner. The scanning area of the device is 400mm by 250mm. The field probe can be turned manually in an angular range of 90° to adjust for the desired polarisation angle in the scanning plane.

A Rohde & Schwarz vector network analyzer ZVCE has been applied in the experimental set-up. The optical signal of the field probe has been converted to a microwave signal using a Tektronix Optical-to-Electrical Converter SD-43. The application of additional amplifiers at the transmitter and receiver site yields a dynamic range of 60dB.

Figure 6: Planar near field scanning of a patch antenna array

To test the experimental set-up, the near field distribution of a five element linear microstrip patch antenna array has been scanned 20mm above the antenna substrate. Figure 6 shows the field probe above the central antenna element of the array.

The antenna elements are designed to produce a linear polarized, y-directed far field. They operate in their fundamental resonance mode and are excited individually by probes from the rear side of the substrate. The distance between neighbouring antenna elements is a half of the free space wavelength.

Only the central element of the antenna array has been excited while field scanning process, all other antenna ports have been left open. The measured (copolar) y-component of the electric field distribution is depicted in figure 7. The scanning raster was choosen to 3x3mm, which is about 2% of the free space wavelength. The location of the substrate edges are marked by white dash lines in the image. Because of the limited scanning area, only a part of the antenna array is visible.

Figure 7: Measured distribution of the y-component of the electric field, normalized to maximum
The mutual electromagnetic coupling effect between antenna elements of the array is clearly recognizable in figure 7. The bright patches at the positions of the unfed antenna elements indicate their strong spurious excitation by the central antenna element.

6 Equivalent magnetic current source reconstruction

The measured E-field distribution has been used to determine an equivalent magnetic current distribution of the linear antenna array (see [8]). The y-component of the electric field $E_y$ in the measurement plane can be expressed as the result of a two-dimensional convolution of the x-component of a magnetic current density distribution and Green’s function for magnetic dipoles. In matrix notation, this can be expressed as

$$E_y = M_x \ast G,$$  \hspace{1cm} (2)

with the matrix of the measured electric field at the sampling points $E_y$, the unknown magnetic current distribution $M_x$ and the matrix $G$, which contains the sampled Green’s function. The convolution operator $\ast$ produces the central part of the matrix convolution that is the same size as the original matrices. Influences of the field probe to the measured near field distribution have been neglected in this approach.

Unlike in [8], the equivalent magnetic current distribution has been recovered by the application of an iterative deconvolution algorithm, based on the gradient descent method. Severe numerical problems arise when the method of moments is used to solve the integral equation (2) in case of our high resolution measurements.

The result of the deconvolution process is shown in figure 8. The two (horizontal) radiating edges of the microstrip antenna elements are clearly resolved by the deconvolution. Furthermore, radiation contributions from the substrate edges are recognized by magnetic currents which are located nearby the substrate edges. Their amplitude is about 15...20 dB below the magnetic current amplitude of the fed central antenna element.

Figure 8: Calculated equivalent magnetic source distribution of the antenna array, normalized to maximum

7 Conclusions

A new E-field probe particularly designed for near field measurements has been developed. Due to the very small size and the optical connection cable the field distortion can be ignored. A sensitivity of 50µV/m/sqrt(Hz) has been achieved, while the frequency response is flat at least up to 400MHz. Although for higher frequencies no exact frequency response could be measured the general applicability of the probe in the GHz range could be demonstrated.

The application of the optoelectic E-field probe allows the determination of high resolution equivalent magnetic current source distributions of microstrip antenna arrays. The field probe produces very little disturbances to the original electric field of the antenna under test. Thus, it is possible to scan the antenna E-field at very short distances, which facilitates high resolution current source deconvolution.

8 References