MINIATURIZED ELECTRO-OPTICAL E-FIELD PROBE WITH HIGH SENSITIVITY AND OPTICAL POWER SUPPLY

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ABSTRACT

A new E-field probe with small outer dimensions (5×5×5mm^3) is presented. Interconnections to the remote unit are all optical in order to minimize the field disturbance. A VCSEL (vertical cavity surface emitting laser) modulated by the field strength is employed for transmitting the signal to the remote unit. Probe characteristics are calculated using a simple probe model and compared to measurement results. The measured sensitivity is about 50µV·m^{-1}·Hz$^{-1/2}$ in aqueous media at 100MHz, yielding a dynamic range of 130dB (1Hz measurement bandwidth).

INTRODUCTION

For antenna design and verification, hyperthermia applications [1] and EMC (electromagnetic compatibility) measurements it is necessary to measure both amplitude and phase of an RF signal with a bandwidth up to several GHz. For such purposes electro-optical probes using the Pockels effect (e.g. in $LiNbO_3$ crystals) are well established [2,3]. Another approach are active probes containing optoelectronic devices (LED, IRED, Laser) which are modulated by the field. These devices transmit the detected signal via an optical fibre to a remote unit [4,5,6]. The remote unit carries out the reconversion to an electrical signal. For linear operation the optoelectronic devices require a bias current, therefore a probe power supply is needed. In order to achieve minimum probe dimensions a remote power supply is appropriate. An obvious approach is to use a direct electrical power supply. However this is not suitable because of the field disturbance due to the conductive wires leading to the probe. A good alternative is an optical supply [4,6].

PROBE DESCRIPTION

Fig. 1 shows the principle of the probe. The light of a 35W metal halide arc lamp is collimated, focussed and launched into a glass fiber bundle of 2.4mm diameter (numerical aperture: 0.58). The fiber bundle guides the light to a solar cell array which is part of the E-field probe. The array consists of 8 Si cells connected in series. By adjusting the lamp position and thus changing the light power launched into the fibre bundle the bias current I_{bias} of the VCSEL (vertical cavity surface emitting laser) can be set and changed.

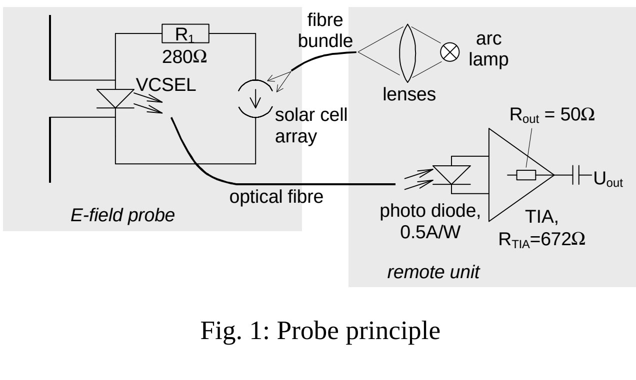

Fig. 1: Probe principle

The resistor R_1 limits the VCSEL bias current at the optimum adjustment of the lamp and lenses, i.e. at the maximum lighting of the solar cells. Furthermore R_1 decouples the antenna and VCSEL from the solar cell array. Basic parameters of the utilized VCSEL (oxide defined aperture with 15µm diameter, provided by Infineon Technologies) are: threshold current $I_{th} \approx 3$mA, wavelength $l = 850$nm, differential resistance $R_{laser} = dU/dI = 40..50\Omega$ ($I > I_{th}$), efficiency $k_{Laser} = dP/dI \approx 0.3$W/A, RIN (relative intensity noise) < -130dB/Hz.

The dipole antenna consists of 2 parallel thin metal plates of 5.5×5 mm² arranged in a distance of d = 5mm (see Fig. 2, dipole electrodes perpendicular to the figure plane). In comparison to thin dipole rods this construction gives a much lower antenna impedance due to the higher capacitance. The antenna signal directly modulates the VCSEL. The whole probe is encapsulated in a polymer, particularly in order to protect the VCSEL from electrostatic discharge (ESD).

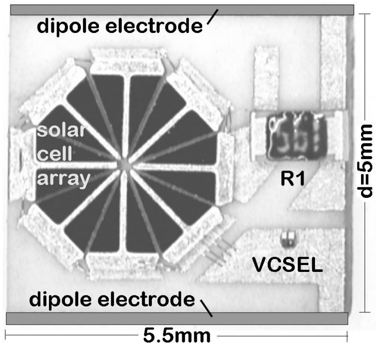

Fig. 2: Top view of the probe carrier substrate

THEORY

The probe was mainly designed for hyperthermia applications (cancer treatment, [1]), i.e. it is designed for use in aqueous media at a fixed frequency around 100MHz. The probe gain (output signal refered to field strength) can be calculated as follows.

The impedance of the dipole antenna is represented by a capacitance C_{ant} of about 3pF in aqueous media. This value may vary by a factor of 2, the exact value strongly depends on the thickness of the encapsulating polymer due to their low permittivity in contrast to the high permittivity of the surrounding water. Furthermore we neglect the parasitic capacitance of the VCSEL and assume the solar cells to behave as a short-circuit at 100MHz (high capacitance). The resulting small signal equivalent circuit diagram is shown in Fig. 3.

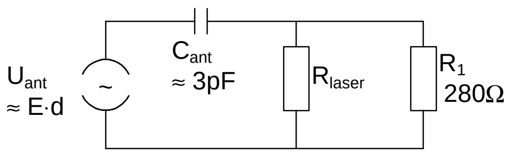

Fig. 3: Simplified small signal equivalent circuit diagram

Because of the geometry of the dipole (‘large’ electrode plates) the antenna source voltage U_{ant} is approximately $E \cdot d$. Actually it may be somewhat higher due to the higher field strength inside the probe which comes from the difference of the permittivities. The AC current through the VCSEL ($I_{laser,AC}$, modulation current) is obtained by

$$I_{laser,AC} = \frac{R_{laser}^{-1}}{R_{laser}^{-1} + R_1^{-1}} \cdot \frac{E \cdot d}{(R_{laser}^{-1} + R_1^{-1})^{-1} + (j2pfC_{ant})^{-1}} \quad (1).$$

The resulting AC component of the photo current $I_{ph,AC}$ and the output voltage U_{out} of the transimpedance amplifier (TIA) are

$$I_{ph,AC} = I_{laser,AC} \cdot k \quad \text{with} \quad k = k_{Laser} \cdot k_{PD} \cdot k_L \quad , \qquad U_{out} = I_{ph,AC} \cdot R_{TIA} \quad , \quad (2)$$

where k_{Laser} is the efficiency $\mathrm{d}P_{opt}$ / $\mathrm{d}I_{VCSEL}$ of the VCSEL, k_{PD} that of the photo diode ($\mathrm{d}I_{ph}$ / $\mathrm{d}P_{opt}$) and k_L stands for coupling losses ($k_L \leq 1$). Inserting the given values and setting k_L = 1 we obtain U_{out} = 0.80mm · E for f = 100MHz. As the TIA has a 50Ω output this corresponds to a probe gain of about -49dB(mW$^{1/2}$/(V/m)).

The AC current through the VCSEL ($I_{laser,AC}$) increases with field strength. Therefore above a certain field strength the VCSEL current temporarily drops below the threshold current. The resulting occurence of harmonics and intermodulation effects determines the upper limit of the probe measurement range. To calculate this maximum field strength we define $P_{opt,DC}$ as the optical DC power of the VCSEL, giving a DC photo current of $P_{opt,DC} \cdot k_{PD}$. The limit corresponds to

$$\hat{I}_{ph,AC} = I_{ph,DC} \quad \leftrightarrow \quad \sqrt{2} \cdot I_{ph,AC} = P_{opt,DC} \cdot k_{PD} \text{ , i.e.} \tag{3}$$

$$U_{out} = \frac{P_{opt,DC} \cdot k_{PD}}{\sqrt{2}} \cdot R_{TIA} \tag{4}$$

For $P_{opt,DC}$ = 400µW this gives U_{out} = 95mV (-7.5dBm). At a probe gain of –49dB(mW$^{1/2}$/(V/m)) this corresponds to a maximum field strength of 41.5dB(V/m) ≈ 120V/m. For $P_{opt,DC}$ = 200µW we have a maximum output signal of -13.5dBm, i.e. a maximum field strength of 35.5dB(V/m) ≈ 60V/m.

As the VCSELs resistance R_{laser} and the antenna capacitance C_{ant} form a high-pass filter with a 3dB cut-off frequency of about 1GHz, the probe gain will increase proportional to frequency (20dB/decade) up to 1GHz. Above this frequency the precondition λ >> probe size is not valid any more, thus the probe is suitable for frequencies up to 1GHz.

MEASUREMENTS AND DISCUSSION

The probe gain, noise and dynamic range were measured at a fixed frequency of 100MHz. For the field generation a quasi TEM cell as described in [7] was utilized. The arc lamp position and lenses were adjusted for $P_{opt,DC}$ = 400µW. Fig. 4 shows the measured TIA output signal U_{out} (dBm re 50Ω) vs. field strength E. The resolution bandwidth (RBW) of the spectrum analyzer was 100Hz and the noise power bandwidth (NPBW) 113Hz.

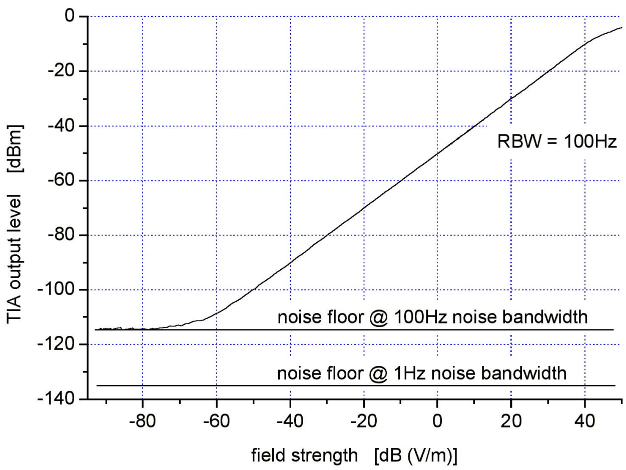

Fig. 4: TIA output level vs. field strength ($P_{opt,DC}$ = 400µW, f = 100MHz)

We obtain an experimental probe gain of -50.0dB(mW$^{1/2}$/(V/m)) in good accordance with the theoretical estimation and a noise floor of -114.5dBm at 113Hz NPBW corresponding to -135dBm/Hz. This gives a sensitivity of -85dB(V/(m·√Hz)) ≈ 56µV/(m·√Hz)) (noise equivalent field strength). The 1dB compression point is reached at a field strength of E_{1dB} = 44dB(V/m) ≈ 158V/m, yielding a dynamic range of 129dB (1Hz measurement bandwidth).

The measured noise of –135dBm/Hz corresponds to an equivalent noise current flowing through the photo diode of 56pA/√Hz. The DC component of the photo current was $I_{ph,DC}$ = 200µA, giving a shot noise of 8pA/√Hz. The noise of the TIA can be neglected. Thus the dominant noise source is apparently the RIN of the VCSEL. With the values above it is –131dB/Hz. Since no stabilization of the solar cell voltage was applied, not only the RIN of the VCSEL itself but also a noisy supply voltage may contribute to the RIN.

The measurements were repeated with different bias currents (P_{opt} = 200, 400, 500, 600 and 700µW) obtained by readjusting the arc lamp position. For increasing bias currents the following can be observed:

- The probe gain decreases. Since the (measured) I-P characteristic of the VCSEL is very linear this is expected to be a thermal effect. As the lighting of the solar cells is increased the temperature of the probe gets higher (all input light power is converted into heat except for the VCSEL output light). This reduces the VCSEL efficiency and therefore reduces the probe gain.
- The noise at the TIA output slightly increases, corresponding to a degradation of the sensitivity. This is expected to be a thermal effect too or an effect due to a noisy voltage of the solar cells.
- The 1dB compression point is increased and thus the dynamic range too, although the noise increases. However the dynamic range is finally limited not just by the probe but also by the TIA.

Due to field inhomogeneities of the TEM cell the measured data of the linearity have an absolute uncertainty up to about 1dB. The relative (differential) precision of the results is not affected. The above measurements have been carried out at 100MHz. Measurements of the frequency response in the range from 70 to 350MHz indicated accordance with the theoretical considerations.

CONCLUSION

A new active electro-optic E-field probe has been presented. All optical interconnections to the remote unit and small probe dimensions of about $5\times5\times5mm^3$ assure minimum field disturbance. The probe is optical powered and employs a VCSEL with a low threshold current for transmitting the measured signal to the remote unit. It features a high sensitivity of about $50\mu V/(m\cdot\sqrt{Hz})$ (noise equivalent field strength) in aqueous media at 100MHz. The 1dB compression point is about 150V/m, giving a dynamic range of 130dB (1Hz measurement bandwidth). The dynamic range is limited by the RIN of the VCSEL.

The probe characteristics were calculated and measured for use in water and aqueous media. Since the probe gain is strongly dependent on the capacitance of the antenna dipol and therefore on the permittivity of the surrounding media, it will decrease by about 30 - 40dB when using the probe in air. The probe has a high-pass filter characteristic. These effects can be minimized by means of a FET preamplifier which acts as an impedance matching device.

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