Miniatrized Fiber-Coupled E-Field Sensor

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Abstract

Results of an optical sensor system for frequency selective E-field measurements in the frequency range from 10 MHz up to 6 GHz are presented. The key component is an electroabsorption modulator that transfers the measured electric field into the optical domain, enabling the transport of the measured signal without any perturbation of the measured field. Further important components are located in the sensor head, including a miniaturized antenna, a low power transimpedance amplifier and a photovoltaic cell (PVC) array. The latter avoids the use of batteries inside the sensor head, as the necessary power is transmitted from a high-power laserdiode inside the remote read-out unit to the sensor head, where the necessary electrical power to drive the transimpedance amplifier is generated by the PVC array. Due to this completely fiber coupled approach of the sensor head the interference with the measured field is minimized. Using a sensor head with dimensions of 10 mm · 8 mm · 2 mm the minimum detectable E-field was less than 0.1 V/m with a dynamic range in excess of 58 dB within the frequency range from 0.01 to 6 GHz.

1 Introduction

The measurement of electric fields with high spatial resolution and high sensitivity is desirable in many technical and medical applications. Currently, several commercial sensor systems are available [1-3]. However, they do not offer the features of frequency selectivity, single field component resolution and high spatial resolution, simultaneously. Especially within the fields of EMC pre-compliance testing and antenna measurements it is essential to have E-field sensors available that operate up to microwave frequencies with the possibility of frequency selective measurements of single field components. Furthermore, the possibility for on board measurements with high spatial resolution during the design and development phase of printed circuit boards is another envisaged market for microwave E-field sensor systems. Obviously, the use of fiber-coupled sensor systems for E-field measurements offers the advantage of a minimized interference together with the potential to obtain frequency selective amplitude and phase information of the measured field [4-6] in the RF frequency range. Thus, the successful implementation of an E-field measurement system, especially with a miniaturized sensor head relies on the availability of efficient small-size electro-optic converters, that transfer the field information from the electrical into the optical domain. This transformation can be performed either by direct modulation of a light source located inside the sensor head or by external modulation using a so called looped-back configuration of a laserdiode that is located in the read-out unit. For operation up to the microwave frequency range the external modulation technique is preferable over the direct modulation with the further advantage that no additional expenditure for thermal stabilization of the sensor head is required. Furthermore, the external modulation is preferably performed by a semiconductor electroabsorption waveguide modulator instead of a LiNbO₃ modulator, as the higher sensitivity of the electroabsorption modulator allows to use devices with significantly shorter interaction lengths. Hence, it is possible to develop sensor systems with a miniaturized sensor head that exhibit a large dynamic range and high sensitivity, together with high spatial resolution. We present the results of a small-size sensor head that utilizes the sensitivity of an electroabsorption modulator linked to a short planar monopole antenna via a GaAs MESFET transimpedance amplifier. Remote powering of the sensor head via an integrated photovoltaic cell array is an additional feature of the sensor system, which allows to control the performance of the E-field sensor by adjusting the bias conditions of the amplifier together with the electroabsorption modulator. Section 2 gives a detailed description of the realized sensor system, before the developed electro-optic key components and the experimentally determined behavior of the fiber-coupled RF E-field sensor system are summarized in the following three sections.
2 Sensor system

The interference with the measured field is of major importance in E-field measurement systems. In order to keep this interference at a minimum level the developed sensor system is split into a sensor head and a remote read-out unit which are connected via optical fibers, as sketched in Fig. 1. The read-out unit contains the laserdiode operating at 1.55 μm, which provides the carrier for the looped-back transmission of the measured signal, and a second laserdiode operating at 0.84 μm, which is used for the remote powering of the sensor head. Furthermore, a broadband photodiode is located inside the read-out unit, which recovers the electrical signal from the optical domain and assigns it to an electrical interface, where the electrical output signal can be measured, e.g. by connecting an electrical spectrum analyzer. The realized read-out unit is shown in Fig. 2(a). This unit is located far away from the measurement location and is connected to the sensor head via optical fiber. The integrated sensor head consists of a planar monopole antenna that has a length of only 4 mm. The signal gathered with this antenna is transferred to a fiber coupled InP based multiple quantum well (MQW) waveguide electroabsorption modulator. A GaAs MESFET transimpedance amplifier with a transimpedance gain of 5 dB reduces the effect of the large impedance mismatch between the small monopole antenna and the electroabsorption modulator, resulting in an improved sensitivity of the sensor system. The drawback that the sensor head requires electrical power to bias the transimpedance amplifier and the electroabsorption modulator, is circumvented by using a GaAs based photovoltaic cell array (PVC-array) that neither significantly adds metallic parts nor increases the size of the sensor head. The arrangement of the different components on the Al₂O₃ substrate of the realized sensor head is shown in Fig. 2(b).

3 Electroabsorption modulator

The waveguide electroabsorption modulator developed for the sensor head is optimized for polarization insensitive operation at a wavelength of 1.55 μm. The device has a MQW structure with 10 pairs of non-intentionally-doped (n.i.d.) strain compensated 10 nm InGaAs wells and 11 nm InGaAsP barriers. The overall thickness of the waveguide is increased to 421 nm by adjacent n.i.d. InGaAsP layers. The optical cladding and electrical contact layers are formed by 600nm n- and p-type doped InP below and on top of the waveguide layers,
The waveguide modulator structure is formed as a 12 μm wide mesa structure with an electrical hybrid coplanar-microstrip metallization. The modulator section is connected to coplanar bondpads via an electrical taper on the semi-insulating substrate. This taper is enabled by a polyimide sidewall passivation of the mesa structure. Furthermore, the electroabsorption modulator is integrated with InP V-grooves to simplify the fiber alignment and fixation. The position of the V-grooves with respect to the waveguide is defined together with the formation of the waveguide mesa in a single wet chemical etching step. The etching of the V-grooves is performed as the final step of device fabrication, after the metallization, passivation and etching processes for the modulator structure have been carried out. Defining the waveguide and the V-grooves within one technological step avoids lateral misalignment between the fiber and waveguide, while the vertical fiber position is predefined by the depth and angle of the V-groove. The SEM picture of a realized 100 μm electroabsorption modulator is shown in Fig. 3.

![Fig. 3: SEM picture of realized electroabsorption modulator with integrated InP V-grooves](image.png)

The RF behavior of the fiber coupled modulator [7] is characterized by inserting the device into an analog optical link. For this, light from a laser source at λ=1.55 μm is coupled to the modulator and an electrical input signal from a swept frequency synthesizer is fed to the modulator via high-frequency coplanar probes connected to the coplanar bondpads. The modulated optical signal is detected by a broadband InGaAs photodetector (S = 0.98 A/W) whose output is connected to an electrical spectrum analyzer. In Fig. 4 the measured modulation performance is shown together with the response predicted for the modulator from its equivalent circuit up to 10 GHz. The 3 dB cut-off frequency in the range of 4 GHz is in very good agreement with the simulated response. The measured RF link gain of the analog optical link is -51 dB at a frequency of 1 GHz, with an optical input power of 7 dBm to the modulator. The linearity of the modulator is determined from two-tone measurements. For this two electrical signals at frequencies f1=900 MHz and f2=910 MHz are combined and fed to the modulator. The optical power is modulated with the electrical input signals. Due to the nonlinear behavior of the electroabsorption modulator different intermodulation products are generated. We observed the modulation performance at the fundamental frequency f1=900 MHz together with the adjacent third order intermodulation product IM3 at 2f1-f2=890 MHz. The experimental results of this two-tone measurement are shown in Fig. 5.

![Fig. 4: Measured frequency response of realized electroabsorption modulator](image.png)

![Fig. 5: Experimental results from two-tone measurements](image.png)

A linear increase of the RF output power at the fundamental frequency can be observed over a large range of electrical input power. The 1 dB compression from the linear relation between electrical input power and electrical output power of the analog optical link is observed for an input power of 3 dBm, resulting in a linear dynamic range of 97 dB. Furthermore, the third order intermodulation product is not visible above the noise floor of the electrical spectrum analyzer up to an electrical input power of -23 dBm, which results in a spurious free dynamic range (SFDR) of 71 dB for the modulator within the RF optical link.
4 Photovoltaic cell array

To enable optimum functionality of the sensor head the integrated transimpedance amplifier was designed as low power device with a DC power consumption of 40 mW at a bias voltage of 4 V. This power is provided by a GaAs based PVCs. The photovoltaic cells are optimized for monochromatic operation at $\lambda=840$ nm using an AlGaAs/GaAs pn-double heterostructure. The active GaAs pn-junction is embedded between p- and n-doped transparent AlGaAs layers for optimum localization and transport of the generated photocarriers. Adjacent to these AlGaAs layers highly p- and n-doped GaAs contact layers are located, to enable the realization of low resistivity ohmic contacts for minimum losses of the PVC. As a series integration of several cells is required to provide the desired output voltage of 4 V the layer structure is grown on a semi-insulating (s.i.) GaAs substrate. In Fig. 6 the photograph of a technologically realized PVC-array is shown. The array consists of a series connection of six similar PVCs, which are arranged in a circular formation. The circular shape allows optimum coupling performance from a circular diameter fiber core with large diameter to the array. Furthermore, maximum efficiency can be achieved as the optical intensity is equally distributed between all cells. The cross-section through a single cell is shown in Fig. 7. The connection between two PVCs is performed using a polyamide passivation of the mesa structure to guide the p-type contact down to the s.i. substrate and connect it to the n-type contact of the following cell. The antireflection (AR) coating on top of the cell is realized using a $\lambda/4$ SiO layer. The reduced surface reflectivity increases the efficiency by almost 50 %. Typical experimental data of the realized PVC array is shown in Fig. 8 for different optical input power together with the load line from the specified DC input impedance of the transimpedance amplifier. Obviously, the necessary power to bias the amplifier is easily provided from the PVC-array when it is supplied with an optical input power of 370 mW, resulting in a conversion efficiency of 11 % for this operating point. Furthermore, the linear relation between the optical input and the maximum electrical output power of the fiber coupled PVC-array, shows that almost no saturation effects occur. This is also visible from the maximum achievable conversion efficiency $\eta$ of the fiber coupled PVC-array, as depicted in Fig. 9. As the maximum output power is achieved at bias voltages slightly above 4 V the maximum conversion efficiency of the fiber coupled array increases even up to the range of 14 % with a slight decrease at higher optical input power. The maximum efficiency of single PVCs is well above 25 %.

Fig. 6: Realized PVC-array

Fig. 7: Cross-section of single PVC

Fig. 8: Measured electrical output power vs. output voltage

Fig. 9: Maximum conversion efficiency of fiber coupled PVC array vs. optical input power
System experiments

The performance of the fiber-coupled E-field sensor is analyzed with respect to the minimal detectable electric field and the dynamic range of the system within the frequency range from 10 MHz up to 6 GHz. For this measurements the output of the read-out photodiode is characterized using an electrical spectrum analyzer with a resolution bandwidth of 1 Hz. In a first measurement different electrical field strengths are applied to the sensor head and the minimum detectable electric field is determined from the input field at which a signal to noise ratio of 1 is reached. The results of the measured sensor sensitivity is shown in Fig. 10. The minimum detectable field strength $E_{\text{min}}$ is below 100 mV/m within the whole frequency range. Maximum sensitivity is achieved at 0.9 GHz with a minimum detectable field strength of 16 mV/m.

![Fig. 10: Sensitivity of fiber-coupled E-field sensor](image)

Further important information about the sensor performance is obtained from the dynamic range of the sensor system. This dynamic range value of the system is determined by increasing the input field strength, until the output signal at the read-out photodiode shows a 1 dB derivation from the expected linear increase. The input field strength at this 1 dB output power compression point is $E_{\text{1 dB}} = 78$ V/m. The dynamic range is calculated from the ratio between $E_{\text{1 dB}}$ and $E_{\text{min}}$ within the above mentioned frequency range. The measured dynamic range in dB vs. frequency is depicted in Fig. 11. The maximum dynamic range of 74 dB is achieved at the frequency of highest sensitivity with dynamic range values remaining above 58 dB from 10 MHz up to 6 GHz. The coverage of almost three decades of electrical input field strength within a broad frequency range is comparable to commercially available systems [2,3].

![Fig. 11: Dynamic range of fiber-coupled sensor](image)

Conclusion

A fiber coupled E-field sensor with a sensitivity better than 0.1 V/m and a minimum dynamic range of 58 dB within the frequency range of 10 MHz up to 6 GHz has been realized. As electro-optic key components for the sensor head of this system an InP based 1.55 μm electroabsorption waveguide modulator and a GaAs based photovoltaic cell array have been developed and technologically realized. Due to these electro-optic components optical signal and energy transfer can be realized between the sensor head and the remote read-out unit. Thus, a small-size field probe can be realized with minimum interference of the measured field, but with high sensitivity and spatial resolution.

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References


