Development of Optical Electric Field Sensors for EMC Measurement

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Abstract— **This paper details more than a decade of optical electric field sensor development resulting from collaboration between NPL and Seikoh Giken (formally NEC Tokin). It discusses the technical difficulties of developing such sensors for EMC applications and highlights the excellent performance that can be achieved.**

Keywords—EMC, Optical Electric Field Sensors, Lithium niobate, Mach-Zhender, Pockel's effect.

I. INTRODUCTION

Electric field measurements in EMC are required to measure the radiated emissions from a device and to calibrate the field levels for immunity tests. Typically, broadband antennas are used for emission measurements and diode-based field sensors are used for calibrating field levels for immunity tests. Antenna performance may be affected by coupling effects with the cable and to the surroundings. In the case of broadband antennas, the position of the phase center (that is the effective measurement point) may change with frequency. Both of these factors will contribute to the measurement uncertainty. The physical size of the antenna can limit the environments in which it can be used and the cables can be hazardous in environments where high voltages are present. Field probes are smaller and less perturbing than antennas and can be optically linked to the meter unit but these probes usually use a diode or thermistor to rectify the radio frequency (rf) signal so that the spectral data and phase information of the signals is lost.

Time-domain optical electric field sensors transmit the received rf signal from the electric field sensor over a fibre-optic link as amplitude modulation of the optical carrier. Thus, the optical electric field sensor combines the functionality of an antenna in that both the amplitude and phase of the measured signals are measured, with the small and minimally perturbing nature of the field probes. The use of fibre optic cables facilitates their use in high voltage environments, and allows the signals to be transmitted over hundreds of metres without significant signal loss, which is not the case when using coaxial cables at microwave frequencies. This paper details development of these sensors that resulted from collaboration between NPL and Seikoh-Giken (formally NEC-Tokin) and their application to EMC measurements.

II. PRINCIPLES OF THE OPTICAL ELECTRIC FIELD SENSOR

Optical electric field sensors transfer the measured rf signal over a fibre optic cable as amplitude modulation of the optical carrier, which is achieved using either direct modulation of laser source or external modulation using an electro-optic modulator. With direct modulation sensors, Fig. 1a, the rf signal is used to modulate the laser driver voltage, resulting in modulation of the laser output. In this case, the sensor head must contain the lasers, batteries and control circuits in addition to the antenna elements. The advantage of this arrangement is that the sensitivity of the field sensor is not dependent of the polarization state of the light in the system. An example of a direct modulation field sensor is the Thales Melopee CSF-ET2003, a 3-axis field probe operating from 10 kHz to 2.5 GHz, and with a noise floor of 0.5 V/m and a dynamic range of 40 dB. The sensor is a cube 70 mm by 84 mm by 85 mm containing three laser diodes, control electronics and seven AAA batteries which give approximately one hour continuous measurement capability. More recently, a miniature direct modulation sensor was developed based on vertical cavity surface emitting lasers (VCSEL) powered optically via a photo-voltaic cell [1].

Field sensors based on external modulators have an interferometer structure infused into an electro-optic substrate, commonly lithium niobate or gallium arsenide. In these materials, the refractive index changes with applied electric field due to the Pockel's effect, so the effective path lengths of the two interferometer arms can be changed by applying the electric field differentially across them, and this results in amplitude modulation of the optical carrier. There are two types: Transmission type (Mach-Zhender interferometer), Fig 1 b, which has separate input and output fibers and reflection-type (Michelson interferometer), Fig. 1c, which has a single input/output fiber. The principle advantage of the reflection type modulator is that the sensor element can be located near the tip of the probe, which facilitates field measurements close to sources and re-radiating surfaces. However, the system requires the addition of an optical circulator to separate the forward and reflected signals, and it is more difficult to fabricate the modulator chip due to the angled mirrored surface. Field sensors based on external optical modulators do not require a power supply for the sensor head and are very non-perturbing. However, their sensitivity is dependent on the polarization of the light at the input to the modulator, and this must be maintained constant.

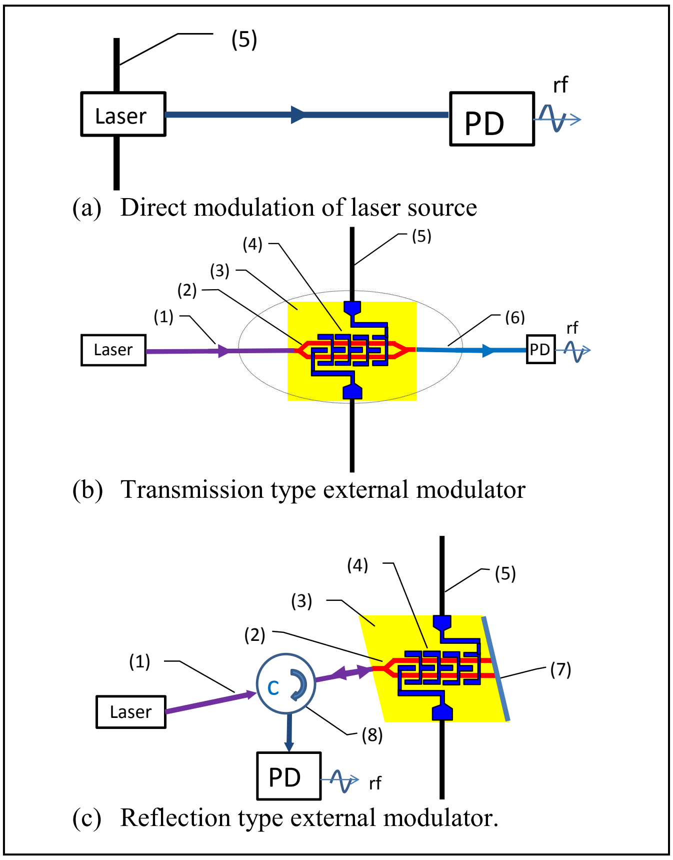

Fig 1. Showing three types of optical electric field sensors (a) Direct modulation of laser source, (b) transmission type external modulator and (c) reflection type external modulator In the diagrams (1) is polarization maintained fibre, (2) is optical waveguide, (3) is the lithium niobate substrate, (4) is the electrode structure, (5) antenna elements and (6) is single mode fibre, (7) is a mirror and (8) is a circulator. PD is the photo-detector.

Whilst the principles of the optical electric field sensor are simple, its implementation is problematic. Achieving high stability and repeatability for the systems is difficult, particularly as measurements may be required in environments that are not temperature controlled, for example an open area test site (OATS). The main reason for this is that the modulator is birefringent, so the modulation depth and therefore the antenna factor for the sensor will depend on the polarization state at the input to the modulator chip, and this is difficult to maintain constant. The rf output signal from the photo detector is weak and must be amplified (typically by around 40 dB) before going to the measuring receiver, so that care must be taken to avoid EMC effects, and it may be necessary to shield the photo detector and rf receiver from the electric fields that are being measured to avoid direct pickup effects. Robustness is limited, as the fibre pigtail to the chip is prone to fail if subjected to shocks.

III. Development of Optical Electric Field Sensors at NPL

Seikoh Giken (formally NEC Tokin) had developed an optical electric field sensor [2] to relay terrestrial broad cast signals via fiber optic cable over mountain ranges in Japan. With NPL, this sensor was improved to provide a stable field measurement system which could be used for metrological purposes. Part of the motivation was to provide a stable and non-perturbing field sensor which could be used to compare between guided-wave and free-field standards for electric field at NPL, with the aim of reducing uncertainties for the calibration of field probes and EMC antennas over the frequency range 30 MHz to 1 GHz. To achieve this, the system had to be sensitive enough to calibrate on the open area test site (OATS) at NPL against the standard dipole antennas, but the sensor had to be small enough to allow accurate measurements of the fields inside Crawford TEM cells [3] and waveguides.

The first version jointly developed with NPL was designated the OEFS-2 and is shown in Fig 2. The sensor head had interchangeable half-wave dipole elements and contained an unbiased lithium niobate Mach Zhender interferometer, so that the radio frequency signal was carried as amplitude modulation of the optical carrier. The system used a 120 mW laser source having a wavelength of 1320 nm.

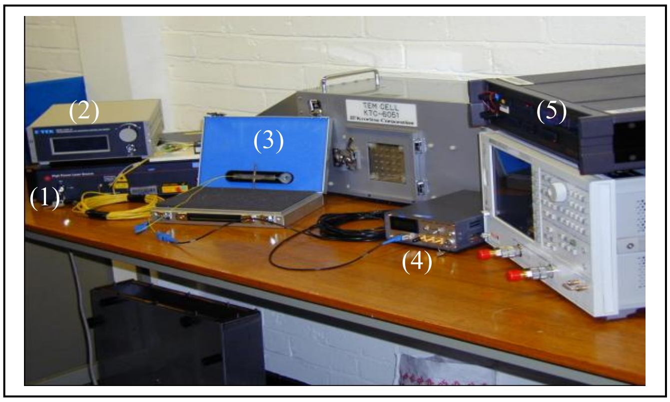

Fig 2. Photograph of the OEFS2 system showing (1) laser source, (2) polarisation controller, (3) sensor head, and (4) photo detector unit. Polarised maintained fibre (yellow) is used between the source and modulator, and single mode fibre (black) is used between the modulator and the photo detector. A voltmeter (5) is used to measure the DC output voltage from the photo detector, and this is used to compensate the antenna factor of the system for variations in the transmitted optical power from the laser to the photo detector.

Initial investigations showed this system was able to detect field strengths down to 0.1 V/m and the sensor was linear over at least a 60 dB dynamic range. However, the antenna factor was only stable to around ± 0.3 dB, largely due to poor alignment of the laser source with the axis of the polarization maintained (PM) fiber and optical connectors in the system were prone to fail due to the high optical power density in the fiber. The system was not robust enough for routine use on EMC test sites as the fiber pigtails to the modulator chip would break if the sensor was knocked or the cables pulled.

A. System optimized for open area test site use (OATS)

The Robust Optical Electric Field Sensor (ROEFS) was developed specifically to provide higher sensitivity, stability and robustness compared to the OEFS-2, and had 60 m of armored fibre optic cables on two cable reels to facilitate use on the NPL OATS; the laser source being mounted on the side of the reel having the polarization maintaining fibre. This arrangement also allowed fixed splices to be used between the laser and modulator, thus improving the polarization alignment and eliminating the problems of connector failure encountered with the previous system. For this system, a more robust sensor head design was developed, Fig. 3, in which the input and output fibres were turned around balsa wood drums to prevent over stressing. The dipole elements, length 120 mm tip-to-tip, were mounted on the front of the sensor and were connected to the electrodes of the modulator chip by thin wires. A fibre optic thermometer was incorporated into the sensor head to allow changes in sensitivity due to the ambient temperature of the modulator to be corrected for, as this was found to be necessary to compensate for the ambient temperatures in the range 0 to 30°C, as encountered on the OATS.

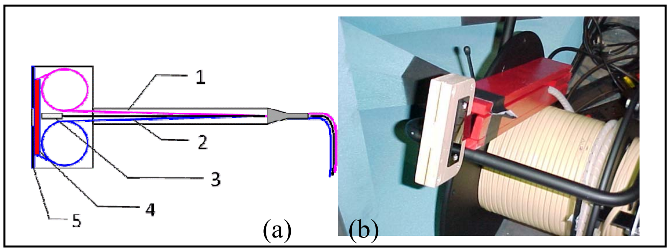

Fig 3. (a) Schematic diagram of improved sensor head design, showing; (1) polarized maintaining fibre to chip, (2) single mode fibre from chip, (3) temperature sensor, (4) modulator chip and (5) dipole antenna elements which are mounted on the front of the sensor. Note that the fibers are wound around drums inside the sensor head to reduce stressing of the pigtails to the modulator chip, and that the sensor housing is constructed of balsa wood to give low reflectivity for EM fields and (b) Photograph of the sensor head and cable drum assembly.

Four condition monitors were added to the system to compensate for the system instabilities. These were: a) the DC photo diode voltage (PD_{V2}), which gives a measure of the transmitted optical power, b) the temperature of the sensor head (T_{SH}), c) circuit temperature of photo detector (T_{PD}) and d) the laser output power. The correction applied, which was derived empirically, is given by

$$Correction\ (dB)=RF(dBm)(1-0.001\,(T_{SH}-20))-20LOG\left(\frac{PD_{V2}(1+0.009(T_{PD}-20)+1.0109(T_{SH}-20))}{PD_{V1}}\right) \quad (1)$$

where RF is the uncorrected RF output level in dBm, and PD_{V1} is the photo diode dc voltage at the time of calibration. The system performed well both in laboratory and site conditions. The antenna factor of the system was 32.6 dBm^{-1} and the frequency response was flat to ± 1.6 dB for the frequency range 50 kHz to 1 GHz. The antenna factor was stable and repeatable to with ± 0.05 dB, even when used on the OATS where the temperature is not controlled. The output connector return loss was better than 15 dB, which gave reasonably low mismatch uncertainties. The system linearity was better than ± 0.05 dB from 50 dBμV/m to 110 dBμV/m, with the sensor able to detect fields as low as 20 dBμV/m with 10 Hz detector bandwidth. From a metrological perspective, this was probably the highest performance optical field sensor developed to-date in terms of its stability, thermal performance and sensitivity, but it was very expensive to make. The measured signals are observed to have additional 1.3 MHz spaced sidebands, which would be an issue for EMC emission. High sensitivity was achieved using narrow (10Hz) rf detector bandwidths, so measuring broadband spectrum could take too long.

B. Miniaturized sensor

In order to allow the measurement of electric fields in close proximity to sources and re-radiating surfaces, a miniature optical electric field sensor (MOEFS) was developed. This was the first of a series of sensors using the reflection type modulator, which allowed the antenna elements to be located close to the tip of the field probe. The modulator chip has dimensions of 6 mm by 3 mm by 1 mm and is encased in resin to form a cylindrical sensor with diameter 6 mm and length 25 mm which is shown in Fig 4.

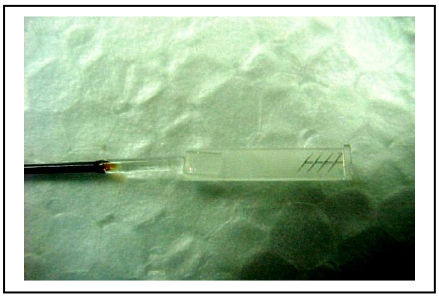

Fig 4. Photo showing single axis miniaturized optical electric field sensor. The length of the modulator chip is 6mm. Note that the fibre splice and mirrored end are angled to reduce multiple reflections of the optical signal

Note that the mirrored end is angled to reduce multiple reflections. An optical circulator was added between the laser source and modulator so that the reflected (modulated) signal for the sensor is separated from the forward (un-modulated) signal and passed to the photo detector. This sensor was able to measure electric fields down to levels of 0.5 V/m and had an operating frequency range of 0.4 GHz to 3 GHz.

C. Development of 3-axis sensors.

A 3-axis version was developed (MOEFS-3), which allow simultaneous measurement of the electric field in three orthogonal directions, and this system was configured for measuring the specific absorption rate (SAR) of rf energy in human body phantoms. Three modulator chips were mounted on the sides of a Δ-beam with the sensors aligned at 54.73° to the axis of the beam so that they are mutually orthogonal. This arrangement yields spherical isotropy within ±1.5 dB, even when the sensor is submerged in liquids. Further, by reducing the interaction length of the electrode structure on the chip the operating frequency range achieved was 0.03 GHz to 9.7 GHz for this sensor. The power from the laser source was divided equally to the sensors and the detector unit contained three parallel circulators and photo-detectors, so that all three channels could be measured simultaneously.

Three versions of the optical sensor are now commercially available which are shown in Fig. 5. These systems use optical switches to select the measurement channel rather than having three parallel optical receivers, since this reduces the cost of the system significantly. The optical wavelength used is 1550 nm, which is safer than 1310 nm and provides similar performance. The miniature sensor, SH-10EL, provides isotropic field measurements over the frequency range 200 MHz to 10 GHz. The cylindrical sensor has diameter 12 mm and length 70 mm, and a measurement range of 0.5 V/m to 1000 V/m in air and can withstand fields up to 10 kV/m. There is also a 30 mm diameter version of this sensor, the SH-03EX that uses longer antenna elements resulting in a 40 dB higher sensitivity, and frequency range is 100 kHz to 3 GHz. The upper frequency range of 3 GHz makes this suitable for monitoring fields from 2G and 3G base stations. A further broadband sensor, SH-10EX, has sensitivity in the middle of the aforementioned sensors, and has a measurement range of 100 kHz to 10 GHz.

Fig 5: OEFS-system- Left to right: Controller unit containing laser source and photo-detector, sensor head type SH-03EX (3-axis E-field) and sensor head type SH-10EL (3-axis E-field).

IV. Applications to EMC Measurement

Optical electric field sensors have been commercially available for more than a decade now, but at present their use in EMC is not widespread. The high cost of these systems is a significant factor in this. Also, it is difficult to make the optical devices robust enough for use in commercial test houses and the long-term stability is generally poorer than that achieved with antennas or diode based probes.

To-date, the main applications for optical electric field sensors is in research measurements. They have been used to evaluate EMC test devices and environments such as the GTEM cell, to measure fields in small enclosures, for example inside cars [4], aircraft, and inside cable ducts and for field measurement in harsh EM environments where conventional antennas or field probes will not operate. Examples of this are measuring the fields from antennas mounted on pylons for HV power lines, assessing signal harmonics in power substations, for electromagnetic pulse testing and for measurements in the bore of the magnetic resonance imaging (MRI) scanner [5]. The later has important application for local specific absorption rate assessment for the patient and for assessing the immunity of active medical implanted devices (AMID's) where the electric field in a body phantom can be measured. OEFS systems have important application to the shielding effectiveness of protective clothing used to shield workers from harmful levels of electromagnetic fields.

V. Conclusions

NPL and Seikoh-Giken have been at the forefront of optical electric field sensor development for over ten years, and this has result in a series of high performance miniature three axis sensors that are commercially available. The principal advantage of these sensors is that they preserve both the amplitude and the phase of the measured signals and they are small and minimally perturbing. However, their high cost has limited the uptake of this technology for conventional EMC-type measurements. These sensors provide a unique capability for spectrum measurements in small enclosures and harsh environments where conventional probes will not operate, for example in the bore of the MRI scanner.

For the future, the number of transmitters on devices is increasing to provide multi-functionality and it is likely that reconfigurable antennas and MIMO systems will become more ubiquitous, which in turn increases the testing time for over-the-air performance and specific absorption rate testing of these devices. Here, the use of optical field sensors, with their flat response and 10 GHz bandwidth, will considerably reduce the testing times since multiple frequency bands can be assessed individually through a single scanning measurement. Also, reduced measurement point schemes to determine the mass averaged SAR can be implemented more accurately than with conventional SAR probes because the phase data is available. There is great potential to use the optical sensors as a direct interface between terrestrial broadcast signals and existing fiber optic communications networks for the purpose of remote monitoring of the EM environment. This facilitates surveillance of radio communications for security purposes and dynamic spectrum allocation for enhanced spectral efficiency. The ability to place multiple modulator tracks on a single chip also offers the potential for development of detector arrays for microwave imaging applications.

Acknowledgment

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