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Photonic electromagnetic field sensor developments

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The paper presents the development of the photonic sensors for electromagnetic field (EMF) measurements. The first applications were limited to the telemetry only. The basic advantage of photonic sensors is the preserved spectral and phase information. Attempts to improve the sensitivity of sensors are illustrated with a Mach–Zehnder interferometer and internal FM modulation of a laser with heterodyne detection. A new concept of the sensor with the use of the Fabry–Perot filter as a wideband frequency discriminator is introduced. Widebandedness limitations due to elasto-optic phenomena in electro-optic crystals and pattern synthesis are mentioned.

1. Introduction

Electromagnetic environment protection requires an effective tool for electric- and magnetic field as well as for power density measurements. Contrary to propagation studies the measurements are in the majority of cases performed in the near-field. Usually, the following EMF parameters are of concern: spatial components of electric field intensity E, magnetic field intensity H and power density S, their polarization, spatial distribution and temporal alternations, modulation, and intensity (RMS or/and peak value). Although at an instantaneous moment of time the EMF is represented by only one linearly polarized E- and one H-field vector that represent superposition of any frequency fringes (including electro- and magnetostatic fields), the spectrum of EMF may be of concern, as well as its spatial and temporal alternations.

The above suggests that a sensor should be wideband, omnidirectional, sensitive enough and of wide dynamic range. In order not to affect the measured field the sensor should be "transparent" to measured EMF.

With some exceptions for E-field pick-up a dipole antenna is in use, while for H-field a loop. In traditional sensors the antenna is loaded with a detection diode, then DC is transferred through a high-resistivity line to a readout. The first disadvantage of the solution is the loss of spectral (and phase) information. This has led to a search for other ways and possibilities of EMF measurements. One of them is the use of photonic EMF sensors [1]. Their merits and demerits as well as the ways of development are outlined in the paper.

2. Introductory solutions

Telemetric applications of photonic techniques are presently offered in many devices, where readings at a distance are required. In EMF measurements an optic data transfer is very convenient in this aspect due to minimization of EMF scatter on the transmission line and its almost ideal transparency to EMF. One of the first solutions using this idea was proposed at the National Bureau of Standards (presently NIST) and then it was developed at Bureau of Radiological Health (BRH) [2]. An output voltage of a standard dipole sensor was lead to a light emitting diode (LED) and then by a optical fibre transmitted to a readout at a distance of 4 m. The device worked within frequency range 915 MHz–10 GHz and within dynamic range 20–100 mW/cm^2.

The concept was developed for the vertical EMF sounding near large transmitting antennas [3]. A standard EMF meter, equipped with an optic transmitter, was carried out by a "Graf Zeppelin" type, 5 m long balloon. An analog signal from its sensor was converted in a DC/AC processor, transmitted down through a 100 m long fiber-optic (simultaneously playing the role of a balloon hold) and led to a recorder. Apart from the transparency to the field, the system, due to galvanic insulation, assured protection of the measuring team and the device against an electric shock, especially while the measurements were performed near HV power lines, charged guy wires of an antenna or to storm-type electrostatic discharges. The device enabled E, H and S measurements within frequency range 25 Hz–10 GHz, with a set of exchangeable sensors for separate frequency and measuring ranges. The carrying ability of the balloon allowed measurements up to 500 m. Since the software and capacity of computers were not sufficient to estimate EMF distribution around a radiation source it was an invaluable tool for experimental studies and checking theoretical data. Even today it is irreplaceable in complex EM environment measurements.

An alternation of optical parameters of some liquid media as a function of their temperature has been studied for a long time [4]. The temperature rise of the media, due to EM energy absorption, was applied to EMF sensing. Contrary to the passive thermal-effects (reflection, attenuation) an active one was developed [5]. A small quantity of a phosphorescent material was excited by a light pulse. Then the decay time of the induced phosphorescence was measured. The time is a function of the phosphor temperature. Phosphor was illuminated and then observed via a optical fibre.

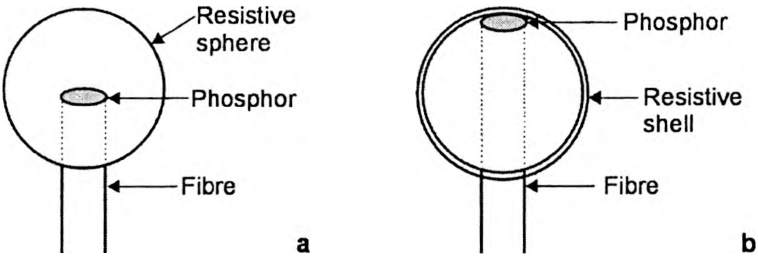

Fig. 1. Thermo-optic EMF probes with a sphere head (**a**) and a shell head (**b**) [5].

In order to pick-up the EM energy the device was immersed in EM absorbing spheres made of different lossy media and in different configuration as shown in Fig. 1.

Flat frequency response of the probe above 13 GHz and its sensitivity of 17 V/m were theoretically estimated and experimentally proven. A disadvantage of thermal probes is, as in the case of the traditional ones, the loss of spectral and phase information. Moreover, their sensitivity, especially at lower frequencies, is not satisfactory; as a result at lower frequencies the traditional solutions have to be used [6]. However, a unique advantage of thermo-optic probes lies in that they enable true RMS measurement in a wide dynamic range. In any other solution it is troublesome, especially in the case of the pulsed field measurement and it may cause remarkable reduction in the measurement accuracy.

3. Classic solutions

Different types of electro-optic and magneto-optic modulators may be applied to EMF measurements. It may be a direct modulation, while measured field is applied directly to a field sensitive crystal or indirect modulation while modulating voltage comes from an *E*- or *H*-field antenna. The applications have already been discussed and their parameters compared [7]. Although reflective modulators [8] or balanced detectors [9], [10] among others were used to increase sensitivity of a sensor the most popular are Mach–Zehnder interferometers [11], [12]. A schematic diagram of the Mach–Zehnder interferometer as a balanced EMF sensor is shown in Fig. 2.

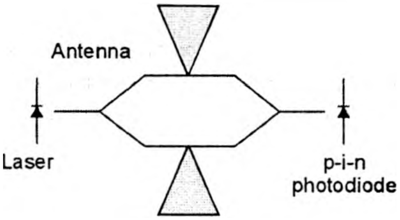

Fig. 2. Mach–Zehnder type *E*-field sensor.

A light beam from a monomode laser is divided into two arms of the interferometer in which their velocity is modulated due to a dependence of the crystal's permittivity on the voltage applied to the electrodes (or rather on the *E*-field strength in the crystal). At the output, as a result of interference of two beams in different phases, an amplitude modulation of the resultant beam is obtained. AM signal is detected and then led to a spectrum analyser or any other indicator. We would not discuss in detail the principles of the interferometer work as it is only an example well known from the literature. However, it is very important here to focus attention on the necessity of converting any other type of modulation (phase, frequency, polarization) to the amplitude modulation that could be simply converted to a HF signal in a photodetector – the voltage of the signal would be proportional to the measured EMF strength.

The solution presented enables any type of interpretation of its output signal. It has full spectral information that permits, for instance, its use as an active wideband receiving antenna, it conserves undisturbed phase information, which allows measurement of the real part of the Poynting vector in any conditions (including the near-field ones), *etc*.

The most important disadvantage of the solution is its sensitivity and widebandedness well below that of the traditional probes. Moreover, the design of the sensor is a bit complex and thus more expensive. Our ways of developing the technique are presented below.

4. Sensitivity

The sensitivity of the sensor depends, first of all, on the electro-optic properties of the crystal applied. Not being technologists we may only express our hope that crystals with lower and lower half-wave voltage will be manufactured in the near future. Our attention has been focused on the most effective use of crystals available now.

The first approach was the use of EMF sensor similar to that shown in Fig. 2. The phase shift δ in an arm of the Mach–Zehnder interferometer is given by

$$\delta = \frac{2\pi}{\lambda_0}\Delta n L \tag{1}$$

where: Δn – refractive index change due to modulating voltage, λ_0 – wavelength in the vacuum, L – active length of the arm.

The phase shift is proportional to L. However, because of frequency limitations the sensor sizes should be possibly small. In order to increase the phase shift in the crystal a multi-transition modulator was proposed [13]. Two walls of the crystal were

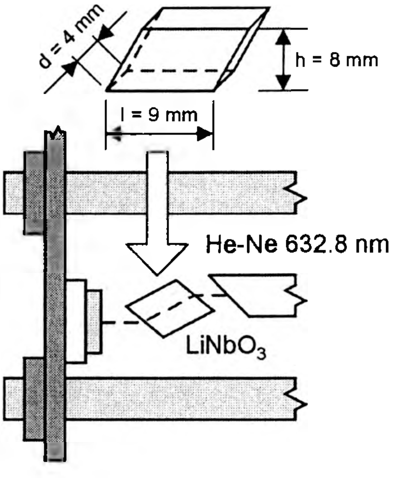

Fig. 3. He-Ne laser with an internal modulator.

covered with a reflecting material and the light beam crossed the crystal several times. Although the efficiency of the procedure was limited by a necessary increase of the modulator input capacitance, an increase of sensitivity approximately equal to the number of transitions was somehow achieved.

A desire to farther increase the sensor sensitivity has led to a change of the external modulation to the internal one. Two major problems, *i.e.*, the laser generation (made more difficult due to the light attenuation by a modulating crystal) and wideband FM detection, were to be solved here.

The rigid construction of two mechanically coupled single-frequency He-Ne lasers forms a coherent optical system. Both lasers are equipped with $LiNbO_3$ phase modulators causing frequency modulation of the lasers. One of them is applied as a sensor while the other one is used for the offset frequency stabilization. A part of the set, with a modulating crystal, is shown in Fig. 3 [14].

The prospective and practical design of the idea presented above is connected with a fast development of diode-pumped microchip lasers (Nd:YAG, $Nd:YVO_4$, *etc.*). A block diagram of the whole dielectric heterodyne sensor is shown in Fig. 4 [15].

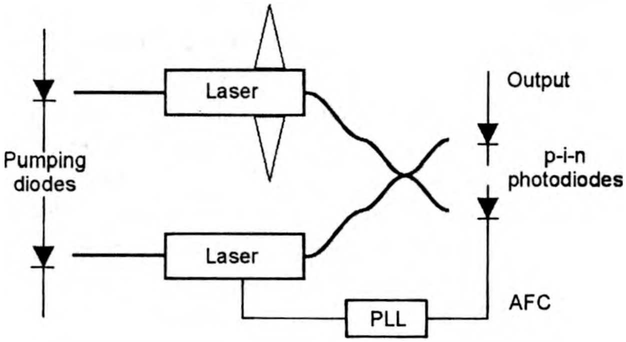

Fig. 4. Superheterodyne EMF sensor.

The system consists of two identical Nd:YAG lasers working in similar conditions. Both of them are excited by pumping diodes via a multimode fibre and associated with phase modulators. A single frequency microchip laser can be tuned over tens of GHz and theoretically allows a similar deviation. One of the $LiNbO_4$ modulators is integrated with a dipole antenna while the other one is used in a phase locked loop (PLL) that stabilizes the IF (intermediate frequency) signal. The IF, after amplification, is detected. Due to the use of PLL the stability of IF on the level of several Hz can be achieved at IF of several tenths MHz. The narrow band FM detection allowed high sensitivity. The sensitivity of the experimental set was below 3 MHz/V. However, the measuring band was limited to the widebandedness of the IF.

The main disadvantage of the heterodyne solution is its complex design. In order to limit the disadvantages an optic frequency discriminator was introduced instead of the heterodyne and FM detection. A block diagram of the sensor is shown in Fig. 5 [16].

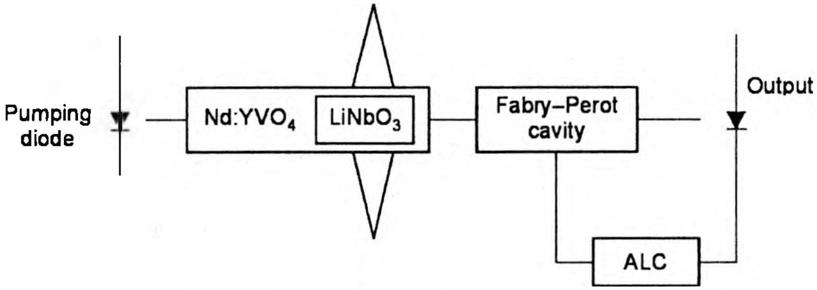

Fig. 5. FM EMF sensor.

The sensor consists of a fiber pumped Nd:YVO$_4$ laser in a cavity of which a LiNbO$_4$ modulator, fed from a dipole antenna, was immersed. The output beam is led to a Fabry–Perot cavity whose resonant frequency is selected in such a way that the laser frequency is set on a side of the resonance curve of the cavity. The cavity plays the role of a frequency discriminator and the widebandedness of the sensor, as well as its linearity and dynamic range, is limited by the quality factor of the cavity. However, the product of the measuring band and sensitivity is here a constant. The larger the slope of the resonance curve, the larger the sensitivity and the narrower the band, and inversely. In the superheterodyne sensor a stabilization of the IF was indispensable. However, it does not allow a control of the absolute frequency of the lasers and their output power that could cause additional errors. In this case, instead of frequency stabilization an automatic level control (ALC) was introduced by way of tuning the cavity. The design of the sensor is much simpler as compared to the superheterodyne; their common disadvantage, due to PLL-AFC (phase locked loop-automatic frequency control) and ALC, is an extension of the lower corner frequency well above time constant of the automatic regulators. Although the sensitivity of the device is still not sufficient and it does not exceed that of the traditional probes (on a single V/m level) it is hoped that its substantial increase is possible and this can be achieved by increasing the stability of a device. Efforts in the field are continued.

5. Frequency range

Some limitations of the measured frequency range were mentioned above. In relation to the lower corner frequency we may summarize that EMF sensor shown in Fig. 2 allows (while its modulator simultaneously plays the role of an "antenna") electrostatic field measurement. In both FM sensors the frequency must be extended as already mentioned.

The upper corner frequency of an EMF sensor is limited by the EMF averaging by the sensor. In photonic sensors the frequency is more rigorously limited by elasto-optic phenomena in electro-optic crystals [17]. A readout of the network analyser which shows measured maxima in a photonic sensor's phase sensitivity due to the phenomenon is given in Fig. 6. The measurements were performed with

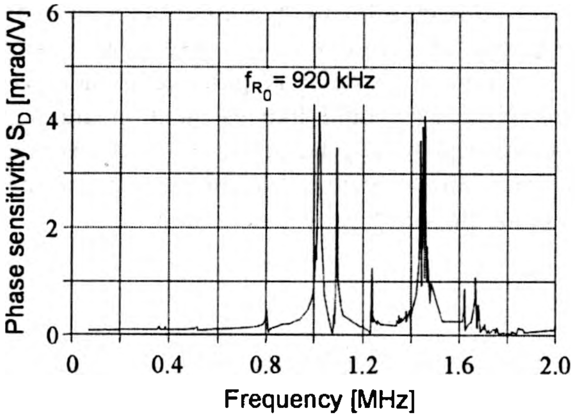

Fig. 6. Phase sensitivity of a photonic EMF sensor.

a large-size model of the modulator, which resulted in a comparatively low frequency of the first resonance.

Irregular frequency response of an optic modulator may be acceptable in many applications, for instance, in telecommunication, in the case of metrology the flat frequency response is of primary importance. The frequency range in the EMF measurements is the widest as compared to metrological applications of other physical quantities. Thus, here the problem of the frequency limitations is the most essential. Unfortunately, the phenomenon leads to the necessity of limiting the measuring frequency band in an artificial way.

6. Omnidirectional pattern synthesis

The omnidirectional pattern synthesis requires an application of a system composed of at least three linearly independent sensors whose squared output signals (voltages) are summed up. The procedure is well known and it may be applied with the use of any type of sensor. Its use may be advantageous when, for instance, separate spatial components of EMF are to be measured. If it is not necessary, there is a possibility of remarkably simplifying the design of the omnidirectional sensor.

The intensity I of the light beam at the output of the Mach–Zehnder interferometer is given by

$$I = \frac{I_0}{2}\left[1 - \cos\left(\pi\frac{V}{V_{\lambda/2}} + \varphi_0\right)\right] \tag{2}$$

where: I_0 – input intensity, V and $V_{\lambda/2}$ – modulating and half-wave voltages, φ_0 – introductory phase shift.

Usually in the Mach–Zehnder interferometer based sensors the working point is chosen for $\varphi_0 = \pi/2$, which assures maximal linearity and sensitivity. The series expansion of the cosine function shows that for $\varphi_0 = 0$ and $\varphi_0 = \pi$ the function is of square character in a range. The case of $\varphi_0 = 0$ has already been discussed [18]. It was shown that for a parallel connection of three sensors it is possible to achieve omnidirectional pattern in one system. Here we would like to mention another possibility, *i.e.*, when $\varphi_0 = \pi$ then the same goal may be achieved by a cascade connection of three sensors. Both solutions assure an expected result, however, at the expense of the sensitivity and a limitation of the sensor's dynamic range.

7. Conclusions

Several new directions in the photonic EMF sensors are briefly outlined. A general conclusion may be drawn that nothing here was achieved for nothing. An increase of sensitivity was at the expense of widebandedness and simplicity of the sensor design, farther attempts to simplify it led back to the band limitation or sensitivity reduction. Finally, a remarkable simplification of an omnidirectional sensor was at the expense of sensitivity, and so on.

A question may be asked: for what purpose this Sisyphean labour has been done? The authors, as old fashioned scientists, may say that for the knowledge itself. To study the possibilities and limitations existing here. However, a more serious answer may be given: although the authors are concerned mainly with the EMF sensors, different aspects and parameters may be of concern in other applications. For instance, in metrological applications the EMF measurement is a unique area where one of the most important parameters is the widebandedness of the modulator (understood as a frequency independent transfer function in a frequency range). In photonic telecommunication the widebandedness is important too, but the sensitivity is of a bit less priority. In other photonic measurements the sensitivity is very important, but the frequency band is usually much narrower, *etc*. And the solutions considered may be successfully applied in each of the areas mentioned above [19].

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