Comparison Between Metallic and Optical Interferometric Sensors for Electromagnetic Field Measurement

Jonathan Daniel Mrquez Lpez
Telecommunications engineering, Bogot, Colombia
Email: jonathanmarquez@usantotomas.edu.co

Abstract—**Many applications around the world use electromagnetic fields (EMF) to accomplish their purposes. Nowadays, to measure these EMF, the use of optical sensors has been rising higher and higher. In this paper, we present a general description of the electromagnetic field optical sensors, more specifically interferometric sensors, with some applications. Also we present a comparison between classical sensors with metallic probes and optical sensors with electro-optical (EO) probes, according to technical parameters showing the advantages of optical sensors beside an economic trend that shows the increase of implementations of this kind of sensors.**

I. INTRODUCTION

The use of wireless technologies has increased around the world. These technologies use electromagnetic fields (EMF) for many purposes like communications, control, research, etc. We can find these electromagnetic fields everywhere, due to this, there is also a increasing need to measure them and have the idea of how they operate and how to control them. All these processes are focuses of research as the development of technology for EMF measurement.

EMF measurement plays an important role in scientific and technical fields as antenna measurement, electromagnetic compatibility (EMC) and specific absorption rate (SAR). The monitoring system for these applications should present high performance sensory devices, which must accomplish certain characteristics as impedance, gain, efficiency, effective area, polarization, bandwidth, durability, good cost-benefit relationship, easy management, assembling and compactness.

Taking these characteristics into account, this paper presents a comparison between systems with classical metallic sensors and systems with optical sensors. It also discusses the advantages that the optical sensors, more specifically the interferometric optical sensors, have above the classical sensors, beside a technical explanation and main application field of this kind of sensors.

II. METALLIC EMF SENSORS

Metallic or classical EMF sensors use metallic antennas to obtain measured values, these devices tend to be simple and cheap. This kind of antennas receives the EMF around them and produce a current or signal proportional to the EMF that gives measuring information about the EMF itself. The antennas used in the classical EMF sensing can take different shapes as dipoles, loops, arrays, micro strip, parabolic or flat antennas[1].

No matter which kind of antenna, the EMF sensor is working with. These antennas are susceptible to external noise from different origins, for example otherworldly sources like galactic noise or solar radiation, radio electric emissions from the earth or the atmosphere, atmospheric electric discharges and also from human and industrial origins. The antennas also have certain kinds of noises which are inherent to them, classified as internal noises, these noises can come from aspects like the antenna or metallic probe temperature or the antenna coupling factor. All the metallic sensors are affected by all these kinds of noise impacting the measurements negatively or making them less accurate. [20].

Some common antennas characteristics are:[1].

- Dipoles and loops:
  - Low gain for Mobile applications, average gain for commercial applications, the average gain values are between 1 and 13.
  - Low directivity, which make them able to perceive EMF from different directions.
- Antenna arrays:
  - Variable gain depending on the array structure and design.
  - As the dipoles or loops they have low directivity, but it is also dependent from the array design.
- Micro strip antennas:
  - Gain around 5.7 dBi.
  - Average directivity, mainly unidirectional but with some side lobes.
- Parabolic antennas:
  - High gain and great bandwidth.
  - High directivity, with a small reception or sensing area.
- Flat antennas:
  - High gain, similar to the parabolic antennas.
  - Average or high directivity depending on the design.

Usually metallic EMF sensors make use of dipole and loop antennas, this kind of antennas has low directivity that enables capturing EMF around them. These antennas have a big operation range of frequencies to measure different EMF. They also have a coupling impedance to match the antenna with the measuring system,as well as, linear polarization(vertical, horizontal or oblique). Depending on this polarization, the antenna is able to perceive the same EMF components as its own polarization.

III. OPTICAL EMF SENSORS

The success of the optical sensors is due to the fact that the conventional sensors are not well-suited in an aggressive environment. They are all immune to electromagnetic interference (EMI) as there is no electrical current flow in them. Over the years, good results have been achieved applying FOS in areas, like hydrophones underwater acousto-sensing and Fiber Optic Gyroscope (FOG). Another really important application, like stringent, is the radiation test. It has proven that the amplitude, temperature and width sensitivity of the Bragg resonance remain unaltered even with high radiation.

Some of the advantages of the optic fiber sensor are[32]:

- High accuracy and sensitivity in comparison to classical metallic sensors.
- Multiplexing capacity that allow distributed sensing applications.
- Optic fibers are made usually from silica and therefore they have some advantages such as resistant to high temperature and hazard environments.
- Fiber optic sensors can be design to be really compact and lightweight making them useful for space-based sensing applications.
- Flexibility for experimentation and applications, the single mode fibers provide a flexible and low loss transmission guide containing and delivering the light, these characteristics makes this kind of fibers reliable to utilize them for remote sensing operations.

It is possible to consider different classification for the optical fiber sensors [2], making a big macro-division in Intrinsic and Extrinsic devices, where in the former, the interaction lies within an element of the optical fiber itself. In the latter kind of sensors, the light beam is ”modulated” by measuring and is coupled by the fibers. It is important to notice that the measuring is performed by an optical device that is usually attached to the fiber by gluing or by fusion. However this is not enough, since the application field’s requirement is important to introduce a schematic division: in-point, distributed and quasi-distributed.

The breadth of improvements in FOS technology has been developing constantly, but today there is a technique used in different fields of physics, as in radio, astronomy, and optics that is the interferometry. Thanks to specific probes, which make estimating the current or some other parameters of the Electromagnetic field possible. The probe should be based on thermal/chemical principle sensible at the modulating wave which will varying the light behaviour in the fiber by acting on a refractive index variation, the general architecture shown in Fig.9 can be changed according to the classical interferometric configurations[3].

IV. OPTICAL INTERFEROMETRIC SENSORS

Optic fiber sensors based on interferometry are based in techniques that make use on principles of optical interference to detect or measure a environmental/physical phenomena through sensing systems made partially or completely with fiber optic components. Historically the optical interference study area dates back to seventeenth century, the rise of the fiber optic interferometry comes from the 1970’s and early 1980’s decades [29]

Inside a fiber optic interferometric sensor structure, usually the light is separated in at least two different ways and at least one of the ways has an interaction with the measured EMF. This interaction of the EMF with the light beam inside the fiber optic would be represented as a phase shift or modulation, which can be detected and measured when the modified light beam interferes with a references light beam which is define for the sensing. The optic fiber interferometric sensors usually have low propagation lost inside the optic fiber, this characteristic gives the interferometric sensors high sensitivity to the measured field. In general this kind of sensor can be used to measure different environmental perturbations such as pressure, vibrations, temperature, acceleration, velocity, force and of course electromagnetic fields.[32]

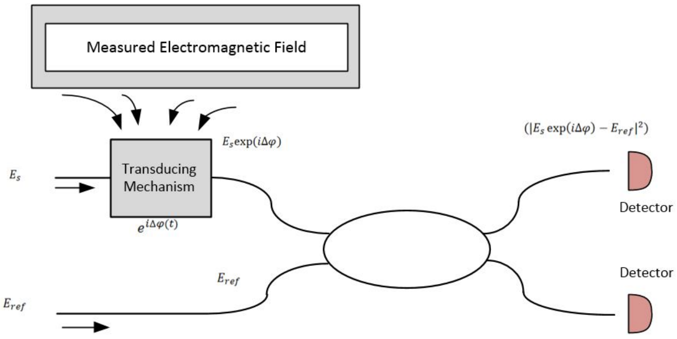

Fig. 1. Generic schematic for a interferometric optic fiber sensor[32].

We can classify the optic fiber sensors into two different categories [31]:

- Intrinsic optic fiber sensors:
  - The light beam is submitted to a modification inside the optic fiber and the fiber itself acts in this case as transducer, in certain section or as a whole. Usually the optic fiber is attached to a special material which acts as transducer in cooperation with the fiber. The intrinsic fiber sensors present many advantages such as efficient design, compact size and high sensitivity.
- Extrinsic optic fiber sensors:
  - Also named hybrid fiber sensors, in this category the light beam is carried by the optic fiber to a device were the light beam is affected and modified in function of the measured field, after, the phase shifted or modulated light beam is inserted back into the same or another optic fiber which connects to a

photo detector where the information is collected, processed and analyzed. This kind of sensors have the advantage that the optic fiber can be seen as a flexible but strong dielectric path for the light beam, which is capable of transport, contain and deliver light for measurement objectives. this characteristic is truly useful in hazard environments were other devices are not able to work properly.

In the extrinsic optic fiber sensors have a large range of applications because the transducer device can be expand as the light is not necessarily contained inside the optic fiber when it is interacting with the measured field, moreover, in the intrinsic optic fiber sensors, some environmental phenomena like temperature or tension would produce a change in the physical properties of the optic fiber itself, resulting in changes in the fiber refractive index or even the fiber length, these changes can affect the light beam inside the optic fiber adding a phase shifting to the light. as we can see in the figure 2 the superior side scheme represents an intrinsic optic fiber sensor and the inferior side scheme represents the extrinsic one.

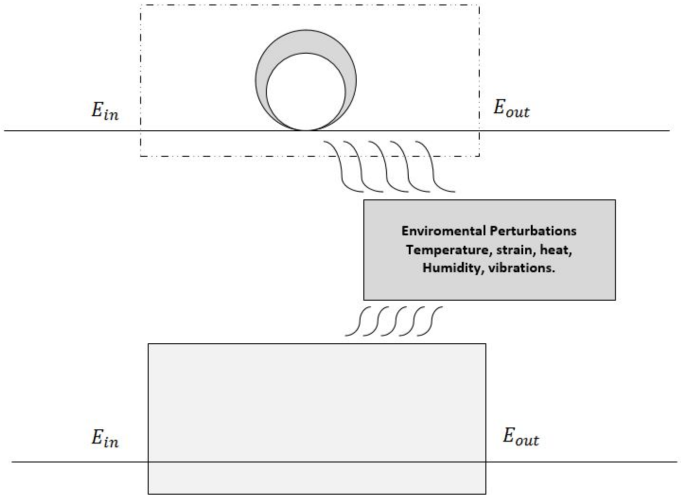

Fig. 2. Generic intrinsic sensor and extrinsic sensor[32].

Nowadays interferometric sensors are widely accepted because they can provide the best measurements taking into account their sensitivity to a range of weak EFM. The interferometric sensors have been investigated and developed because of the increasing work in areas like interferometric demodulation, noise sources, polarization control, multiplexing and EMF measurement, theses topics have raised the need of improving and enhance the features and capabilities of the interferometric sensors[21].

Interference is a phenomenon due to the overlap of radiation fields from multiple sources or by the interaction of different components of the same field. The visibility of the interference phenomenon depends on the characteristics (such as the monochromaticity) of the fields. For example, if two waves are monochromatic, flat and linearly polarized in the same plane having the same frequency and the same amplitude:

$$s_1 = A\cos(\omega t - kz) \text{ and } s_2 = A\cos(\omega t - kz + \phi)$$

the overlap will always be a plane wave with the same frequency and with an amplitude that depends on both the amplitude of the starting waves and their relative phase. So it is obtained:

$$s = s_1 + s_2 = 2A\cos(\tfrac{\phi}{2})\cos(\omega t - kz + \tfrac{\phi}{2})$$

Otherwise if two waves ω_1 and ω_2 are very close, the phenomenon of the beats can be grafted. Let two plane waves:

$E_1 = A_1 cos(\omega t - k_1 r)$ and $E_2 = A_2 cos(\omega t - k_2 r)$ The electromagnetic signal, down to acting through the probe, modulates the refractive index by ”Kerr Effect” as it will be explained shortly, resulting in a modulated intensity transmitted through the fiber [5]. Now, defining the wave intensity I as:

$$I = \langle E^2 \rangle = \lim_{T \to +\infty} \tfrac{1}{2T} \int_{-T}^{T} E^2 dt$$

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\delta)$$

Where $I_1 = A_1^2, I_2 = A_2^2$ and δ is called phase shifting or optical phase and is equal to $\delta = k_1 r - k_2 r + \phi$. The resulting intensity will vary with a sinusoidal behavior starting from a minimum:

$$I = I_1 + I_2 - 2\sqrt{I_1 I_2} \text{ if } \delta = (2n+1)\pi$$

until a maximum value:

$$I = I_1 + I_2 - 2\sqrt{I_1 I_2} \text{ if } \delta = 2n\pi$$

If the pulsed light is purely monochromatic light, the resulting wave would be perfectly sinusoidal. In the case of wide-band light sources, that would not take place, due to what just described is defined the coherence length parameter I_{c} which define the spatial interval in which the light oscillates in a regular manner and consequently is defined the coherence time c which represent the time interval in which is possible represented the wave as a sine wave. I_{c} and c are inversely proportional to the spectral width of the source and the light will be more coherent as much as will be monochromatic. In the interferometry, the phase parameter is a key constraint to be taken into account. In a fiber length L with β the propagation constant:

$$\beta = n_{\mathrm{eff}} k_0$$

where n_{eff} is the average refractive index of the fiber's core and cladding, and k_0 is the wave-number $\frac{2\pi}{\lambda}$
then, the phase can be compute:

$$\phi = \beta L$$

In order to realize an interferometric sensor, a phase modulation must be generated thus a variation over the interference path.

By using non-linear effects for optical fibers; effects which are propagative and which depend on the ”signal” level, and more specifically, on the instant power of the signal. Usually that are undesired effects which influence how much power can be carried by an optical fiber for telecommunication(i.e. WDM systems). In that specific case, it is possible to apply the same physical principle of the ”Kerr Effect” and ”Pockels Effect”, but in a controlled manner varying the refractive index by using a probe which will be described in the following section. As to concern ”Pockels Effect, the refractive index is linearly proportional to the electric field. This effect uses certain crystals which can be of two types: anisotropic crystals or isotropic crystals. The former has the characteristic of not changing the polarization of the eigen axes dielectric [6]; while the latter has a strong dependence between the eigen axes dielectric and the direction of the electric field according the Polarisation State Modulation. In both types, however, the electric field includes birefringence. In the anisotropic crystal, the birefringence phenomenon is linked to a component of the electric field and temperature of the crystal, while in the isotropic sensor, it is linked to two orthogonal components of the electric field[7]. The refractive index, as just explained, has a really related link with the propagation constant β .Now substituting the refractive index variation Δn that takes into account ”Kerr effect” proportional to the square of the electric field:

$$\beta = \tfrac{2\pi}{\lambda}(n_0 + \Delta n) = \tfrac{2\pi}{\lambda}(n_0 + KE^2\lambda)$$

where K is the Kerr constant. Defining $\Delta\beta = \frac{2\pi}{\lambda}\Delta n$ and $\beta_0 = \frac{2\pi}{\lambda}n_0$, is found for β:

$$\beta = \beta_0 + \Delta\beta$$

In the case of no-signal at the probe, the phase of the field defined as:

$$\phi_E(L) = \int_0^L \beta(z)dz = \int_0^L \beta_0 dz = \beta_0 L$$

and the field will be:

$$E(L) = E(0)e^{-j\beta_0 L}e^{-\alpha L}$$

But if such kind of signal will be sensed by the probe, over the fiber will propagate an ”optic power” P, and the phase:

$$\phi_E(L) = \int_0^L \beta(z)dz = \int_0^L(\beta_0 + \Delta\beta)dz = \beta_0 * L + \int_\Delta \beta dz$$

then:

$$\phi_E(L) = \phi_{E_0} + \Delta\phi_E$$

That could be obtained by acting even over L:

$$\Delta\phi = \beta\Delta L + \Delta\beta L$$

In order to vary the L=length which we will call from now on L_{eff}, is possible acting over the factor α, parameter function of the sensed wave, in:

$$L_{\text{eff}} = 1 - \frac{e^{-2\alpha L}}{2\alpha}$$

that will influence the phase as a direct proportional parameter:

$$\phi_{\text{E}} = \gamma P(0,t)L_{\text{eff}}$$

where γ is the non-linear coefficient and $P(0,t)$ the power at instant t.

Thus, the phase changes are converted into variation of Intensity by interferometers. Nowadays, there are several configurations, but the most used are the two arms interferometer Mach-Zehnder and Michelson or the ring interferometer Sagnac or the multiple reflections interferometer Fabry-Perot. In this way, it is possible to measure paths that differ by small fractions of a wavelength (i.e. Differences of order of few nanometers ($\simeq 10^{-9}m$)).
In the Michelson interferometer, the wave is divided in two parts by a beam splitter, the different parts will bounce over two mirror to came back to the beam splitter which forward both the two parts over a screen that combining the two beams will produce the interference.
In the Mach-Zehnder interferometer on the contrary for the Michelson interferometer, the light beams after splitting operation will follow different paths and will be recombined only at the end of each path producing interference.
Sagnac interferometer present as a ring configuration, receive the beam from a point which will be propagated in the clockwise and counterclockwise direction as well, and the interference will be produced when the colliding beams are overlapped in the ring.
The Fabry-Perot interferometer made by two parallel mirrors which built the cavity , produce the interference by multiple reflections in the cavity. When the interference is completely destructive, the interference inside the cavity will be cancelled otherwise if the interference is constructive the beam increase in power after each reflection [3].
Nowadays, the most common applications for this kind of interferometers, compared with their characteristics, are:

- Michelson:
  - Interferometric microscope: High resolution ($< nm$) surface metrology
  - High resolution Lambdameter (wavelength measurement)
- Mach-Zehnder
  - Phase modulators based on a two-wave EO interferometer;
- Sagnac
  - Optical gyroscope central inertial system in aircraft, submarines, missiles,
- Fabry-Perot
  - Resonant EO cavity used as Amplitude Modulation
  - Optical filters both fixed and tunable

There is a wide range of interferometric sensor configurations available to be implemented in fiber form for EMF sensing applications as it is described before, the most widely used configuration is the Mach-Zehnder. Fabry-Perot plus other configuration called Ring Resonator are two-beam configurations are multiple-beam interferometers while the last three are two-beam configurations interferometers. An example is the figure 3 which shows the basic form of the Sagnac two-beam configuration.

The Mach-Zehnder interferometric sensor in the figure 4 has an output transfer function of nonlinear nature, this transfer

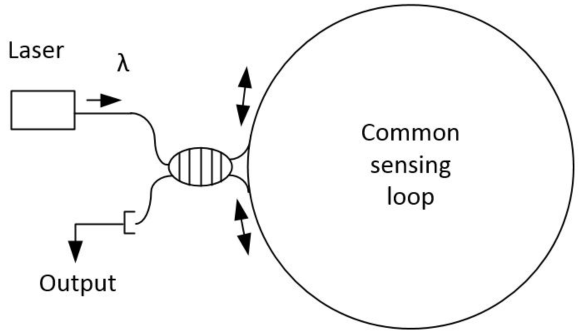

Fig. 3. Sagnac interferometric sensor configurations[21].

function can be described by a cosine interference function. the measurement done with this kind of sensors is done analysing the phase shifting that is proportional to the measured strength, but an aspect to take into account is that such phase is encoded by the interferometer transfer function non linearly into a intensity change in the detector. previous laboratory works on active homodyne phase-tracking schemes[22] were useful in providing means to stabilize the interferometer signal during laboratory experimentation and transducer development and characterization but it was proved unsuitable for almost all the practical applications due to the need to use an electrically active element inside the interferometer.[21]. Later investigations produced some developments using laser frequency modulation-based techniques[23][24] to introduce carrier phase shifting in an unbalanced interferometer which is an interferometer configuration with different beam intensity or different sensing probes length, these new ways were more useful for practical applications because they allowed the interferometer to operate in a passive mode, electrically speaking. The most successful of these approaches is called phase generated carrier which is a scheme with a sine form varying phase carrier which is introduced inside an unbalanced interferometer through a frequency modulation in the optical source. As we have a cosine form transfer function in the interferometer, the phase carrier will result with the harmonics from the modulation frequency. The intensity of the harmonic depends on the sine and cosine interaction in function of the interferometer phase bias. Synchronously detecting the intensity of the first and second harmonic.[25]

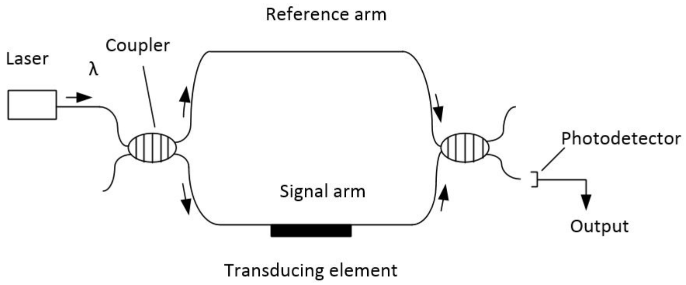

Fig. 4. Mach-Zehnder interferometric sensor configuration[21].

The Michelson interferometric configuration shown in the figure 5 has as main condition that the coherence length has to be greater than the optical path difference between the superposed arms of the configuration. usually for this kind of sensor, interference is considered for coherent waves, where the maximum distance from the laser is related to the spatial cross-correlation between two different points in measured wave for a randomly selected time. The reference and signal beams interfere at the beam splitter. An additional phase shifting between both arms is the cause of changes in the interference bars distribution which is monitored, controlled and measured. The counting of these bar in the detector side, is stored and used to calculate the change of length of the followed optical path. the Number of bars received are proportional to the measured quantity.

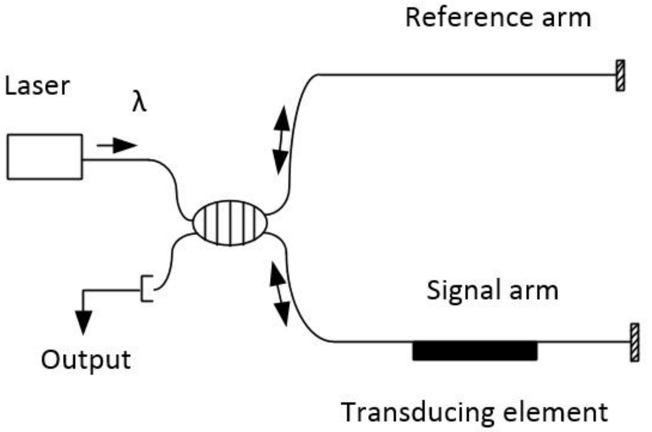

Fig. 5. Michelson interferometric sensor configurations[21].

As explained before there are we can find two-beam or multiple-beam interferometers. Inside the second category we can make spetial mention to the Fabry-Perot interferometric sensor. Some techniques have been developed [26] to set micro-mirrors inside an optic fiber using fusion splicing end-coated fibers. Previous experiments in this field employed single-layer dielectric coatings that after splicing had a reflectances yield minor to 10%. Fabry-Perot interferometers made with these kind of reflectors6 produced interferometers with a two-beam interference bars behavior. Subsequent experiments focused on the use of multilayer films make of TiO_2/SiO_2 located on the fiber ends. Seven-layer coated fibers connected to uncoated fibers by fusion splicing have produce mirrors inside the optic fiber with greater reflectances around 85% therefore, Fabry-Perot interferometers made with these mirrors included produce finesses of ¿20[27]

Other greatly used configuration is the extrinsic Fabry-Perot interferometer7. This structure has two fiber arms, the first one contains a light beam from the source, and the second one has a reflecting surface role, both are put together inside

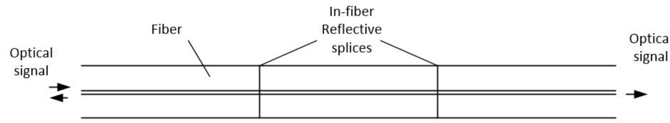

Fig. 6. Intrinsic Fabry-Perot interferometer[27].

an alignment tube. The cavity in the middle of the scheme is formed by a air gap between two uncoated fiber terminations, and the interference signal is detected in the reflected light beam received at the source side of the optic fiber. The most basic extrinsic Fabry-Perot interferometer configuration is compose by two optic fibers stick with resin inside the alignment tube and changes in the internal gap due to EMF applied to the tube are measured by the resulting shifts in the interferometric signal. The limitations of this kind of sensors comes from the ambiguity in the cosine interference bars output of the configuration have been guided by a quadrature phase-shifted extrinsic Fabry-Perot interferometer. In this scenario, two different cavities are formed, with the gap in the first cavity set swiftly larger than the second one with the objective of produce a two different interference outputs that are shifted 90 degrees or $pi/2$ one respect to the other. The resulting sine or cosine phase shifting dependency of both outputs thus ensures that directional ambiguity is negated. [28]

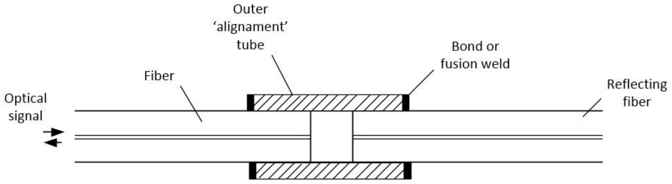

Fig. 7. Extrinsic Fabry-Perot interferometer[28].

Investigations made by Sirkis et al., produced a variation of the Fabry-Perot compact interferometric sensor, this variation is named "in-line fiber etalon" [33] shown in the figure 8. This configuration has both optic fibers connected directly to a section of hollow core fiber through fusion splicing. This setting creates a special sensor without the physic discontinuities of the normal extrinsic Fabry-Perot interferometer.

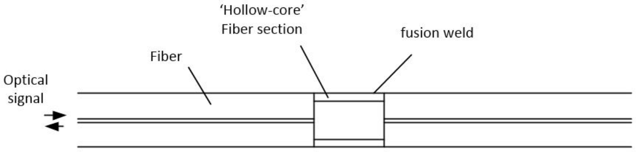

Fig. 8. Fabry-Perot interferometer in-line fiber etanol[21].

The importance of an interferometer lies in the possibility to select the frequencies transmitted, compared to those accidents. In general, an interferometric measure is employed in precision industry because the optical phase measure is a parameter very delicate even if is possible find applications into high power fields[8].

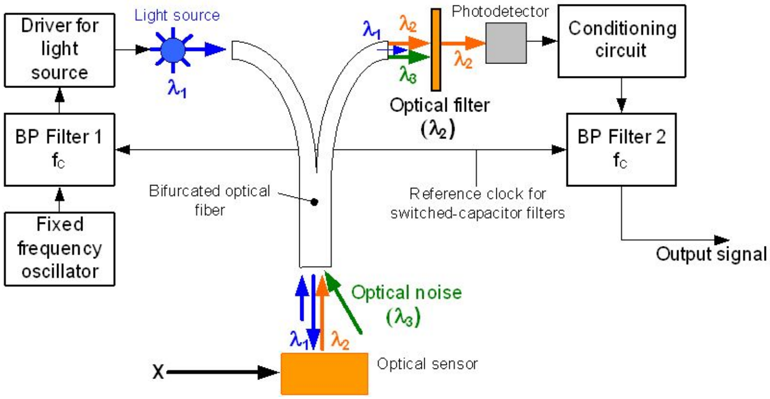

Fig. 9. Architecture of an optical fiber measurement system[9].

V. APPLICATION

Measuring systems for electromagnetic fields as the interferometers described above, they are not sufficient to assess the parameters of an electromagnetic field if they are not provided of accurate probes. Nowadays in relation to the field of application, there are several different types over different technologies.
Besides, with the progress of technology toward optical fibers as expressed in this paper, plays an extremely important role even the sampler envelope for the conversion A/D and type of digital signal processing9. The field sensor utilizes Pockels effect [10], whereby the refractive index of a material changes linearly with applied electric field.

Electro-optical (EO) systems give an answer to the problem. EO probes are intended to perform the characterization and testing of applications such as the antenna's measurement and another important application nowadays, the Electromagnetic compatibility (EMC) [11]. Which may be of concern to the antenna's measurement is identifying crystal probes($1mm^3cube$)[7] with a linear variation of the refractive index with the applied electric field. The Pockel's effect is still used for sensor [12] as lithium-niobate-based ($LiNbO_3$) electro-optical sensor [13], used in EMC applications. The light beam coming from an optical source will bounce over the dielectric mirror at the end of crystal and come back toward the analyser and conditioning circuit(Fig.10), but while the beam crosses the crystal, it will be influenced by the Pockel's effect, as just explained, the refraction index will be changed according the EM wave sensed by the crystal. Moreover, several configurations based on the different interferometers are possible. Based on the same principle are the EO sensor used in the medical field for photo imaging in the monitoring of the specific absorption rate (SAR) [14]. The optical electric field sensor has much higher sensitivity for SAR measurement than thermometers, and the measurements are much quicker.

Therefore this three-dimensional high-resolution optical analysis is rapidly growing due to the modality, that is non-invasive in site and in real time.

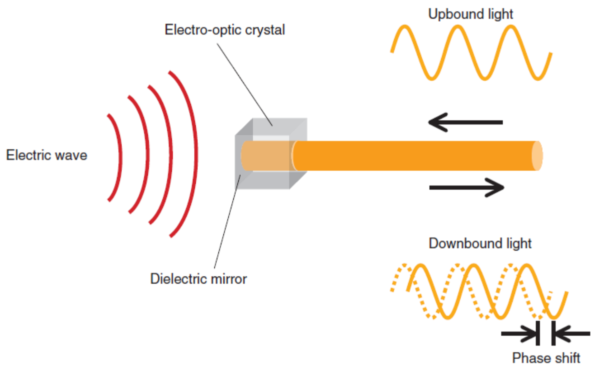

Fig. 10. Pockels effect: Basic principle of electric-field measurement [4].

The EMF can measured also indirectly, the figure 11 shows the configuration of a reflectometric interferometric sensor array which response to strain applied on the fiber, the interferometric response is given by:

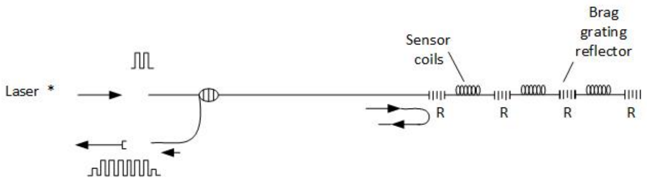

Fig. 11. Interferometric sensor array with fiber Bragg grating reflectors [21].

$$\phi = (2nL\pi/\lambda)[1-(n^2/2)(P_{12}-\mu(P_{11}+P_{12}))]\epsilon$$

Where n is the optic fiber index, L is the optic fiber length, ($P_{\mathrm{i,j}}$ are the Pockel's coefficients of the strain-optic tensor, μ is the fiber Poisson ratio and ϵ is the optic fiber current strain. This configuration allows to measure EMF by converting them into optic fiber strain[34][35]

VI. Discussion

Taking into account the main parameters and characteristics of the EMF sensors[16], we can declare the advantages and disadvantages of the different kinds of probes, metallic antennas and exclusive optical probes like is shown in the Fig. 12 and 13.

A. Spatial Resolution

The EO probes give a more accurate measuring than the antennas regarding the spatial aspect, the difference is in the order of meters. This means that the error during the measuring is less with EO probes than with classical antennas.

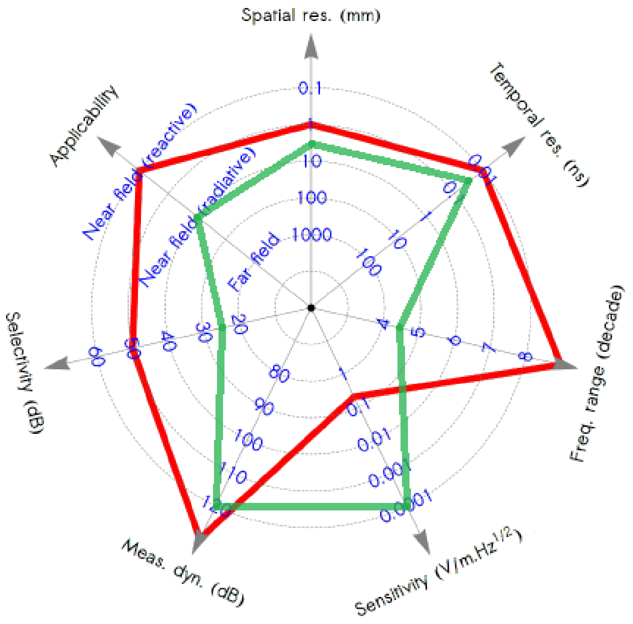

Fig. 12. Classical sensor(Green line), Optical sensor (Red line).

B. Temporal Resolution

The EO probes have a better time response than the antenna measuring the impulse response, although the different is not big (ps). This parameter does not give a difference between both methods, but it should be taken into account when the application requires really high adaptability to the changes in the environment.

C. Frequency Range

The classical antennas are allowed to work in a restricted range of frequencies because of the physical limitations, they have smaller ratio of frequencies between the upper and lower cutoff frequencies, instead of that, the EO probes allow to work in many frequencies, making them suitable to work in many applications that the antennas not. In the market, for antennas measurement, there are devices with EO probes with frequency range between 10 KHz and 110 GHz, for SAR, the range is between 30 MHz and 6 GHz, and for EMC, the frequency range is between 26 MHz and 40 GHz.

D. Sensitivity

This aspect is the only one in which the antennas are better than the EO probes. The antennas are able to perceive from 100 to 1000 times smaller EMF than that of the EO probes, in case that the EMF is not strong enough, the antennas offer better performance than the EO probes to obtain measuring values. In antenna measurement, depending on the medium, the sensitivity change. In the air, the fiber optic probes have sensitivity minor than 500 mV/m, and in the water, it is minor than 50 mV/m while the antennas have sensitivity minor than 20 μV/m in water and minor than 400 μV/m in air. For SAR applications the antennas have sensitivity around -60 dB while the EO probes have a sensitivity around -25 or -30 dB.

E. Selectivity

The EO probes allows the measuring system to separate the objective signal from other interference components better than the antennas, during the measuring there are orthogonal field components that can be avoid, the EO probes allows better rejection to these components than the classical antennas.

F. Applicability

The antennas are not able to give measuring values for near field, because in this EMF's section,the EMF measurement is done near to the antenna meaning the magnetic and electric field are really close to each other, while the EO probes can present qualitative values for near field measurements allowing the measuring and control of this section of the EMF.

Also, for the choice of a specific EMF sensor we should consider certain essential parameters to measure EM fields correctly, for example, which region of the field are we measuring? (near field region or far field region), which it is the environment or medium in which the EMF is propagating? (Vacuum, Water, etc), are there in this medium many electromagnetic interferences(EMI) or high magnetic field?, which kind of EMF are we measuring? (constant, periodic, pulses form, single impulse form), how many components of the EMF are we interested in?, which kind of measures are we doing? (remote or local measures); All this parameters must be taken into account for the selection of a EMF sensor, the Fig 13 shows the relation of these parameters in a double axis comparison, the first axis between classical/metallic/conductive probes(antennas) and optic/dielectric probes, the second axis between metallic/galvanic links and optical links.

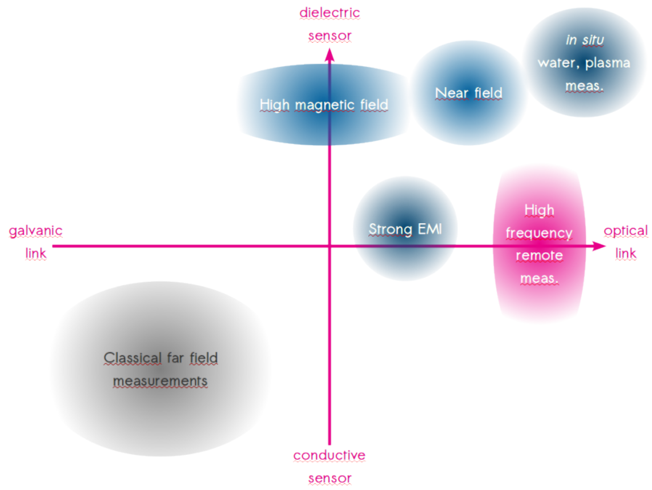

Fig. 13. EMF sensor application field.[15].

Both kind of probes can measure amplitude and phase, detect the EMF variations and preserve the EMF frequency information, but the EO probes present better performance than the antennas as well that the optical link with the metallic link, the antennas presents regular spatial resolution, limited bandwidth and high inductive interference due to the antenna material while the EO probes just have a limited sensitivity[17], these aspects make the EO probes more reliable than the antennas for EMF measurement in general.

VII. ECONOMIC TREND

According to market research report[18], due to the great features for this kind of sensor will be a rapidly increasing behavior in the market and the use of fiber optic sensors will reach \$3.39 billion in 2016 (Fig. 14). Today between the major competitor, there are: Luxtron, Asea, York Sensors, Photonetics, Metricor, Acuifiber and Babcock, and Wilcox will have been familiar to fiber optic sensor. Sensor for SAR are built from Kapteos, Seikoh Giken (formally NEC Tokin) and NPL.

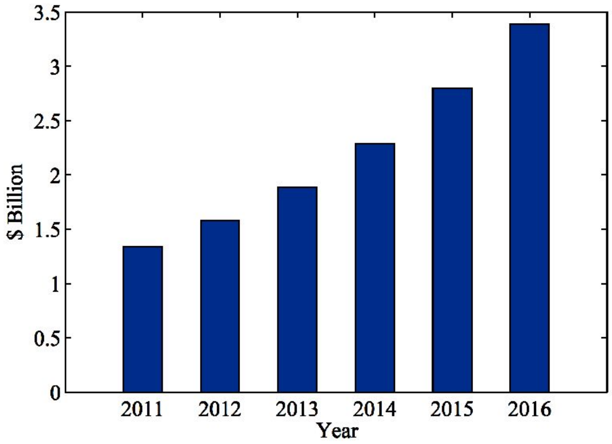

Fig. 14. Increasing trend of market of fiber optic sensors[19].

VIII. CONCLUSION

Optic sensors presents superior performance in many technical aspects than the classical electronic sensors, in comparison with the sensors with metallic antennas that present noise and different limitations due the material of the probes. Optical sensors present better accuracy, response time, lower power consumption, low cost, adaptability, etc, the antennas just have better performance about sensitivity than the EO probes but because of this the antennas are more affected by interferences. All these characteristics make the optical sensors far better choice than the classical ones. Depending on the application in the market are available an unknown number of optical sensors with different features(cost, bandwidth, adaptability, etc), each of them made to measure EMF in different ways, allowing many options to choose the appropriate one to any projects.

The optic interferometric sensors described in this paper are characterize by its complexity. Usually they are implemented in mobile platforms or inside one-person carrying devices, each of them has a different performance and application. however these sensors can be put together to build interferometric sensor networks to improve the performance of the EMF measurement system. It is a fact that the optic fiber sensors based in interferometry have very high, specially in comparison with the metallic sensors, an important task is the capability to differentiate the environmental ”noise” coming from factors like fiber optic tension, pressure, temperature, etc. In principle all these factors can produce variations in the length or fiber refractive index, making more difficult to differentiate the measured EMF field from other perturbations, the most appropriate solution to this problem is a good design of an appropriate more selective transducer mechanism capable to differentiate the measured field from the other perturbations.

Even, if the optic fiber sensor have a better performance than the classic metallic sensors, their relatively higher cost in proportion to these classic low cost sensors is still a wall to pass through to get a better widespread adoption for the optics fiber sensor technology. The optoelectronic area has continued to progress over the last decades resulting in a cost decrease for components such as laser diodes, detector

REFERENCES

[1] C.A.Balanis, Antenna Theory: Analysis and Design, 2on Edition John Wiley, 1997

[2] Eric Udd, William B. Spillman, Jr. Wiley, ”Fiber Optic Sensors: An Introduction for Engineers and Scientists”, 7 oct. 2011 - 512 pages.

[3] Sensors (Basel). 2012, 12(3):2467-86. doi: 10.3390/s120302467. Epub 2012 Feb 23. Interferometric fiber optic sensors. Lee BH1, Kim YH, Park KS, Eom JB, Kim MJ, Rho BS, Choi HY.

[4] Hiroyoshi Togo, Shoji Mochizuki, and Naoya Kukutsu, ”Optical Fiber Electric Field Sensor for Antenna Measurement”, NTT Technical Review, Vol. 7, No. 3, 2009.

[5] Wild, G.; Hinckley, S., ”Acousto-Ultrasonic Optical Fiber Sensors: Overview and State-of-the-Art”, in Sensors Journal, IEEE , vol.8, no.7, pp.1184-1193, July 2008.

[6] Belhadj, N.; LaRochelle, S.; Dossou, K., ”Analysis of birefringence and eigen-axes orientation resulting from the interplay between initial and form birefringence in UV-illuminated fiber,” in Lasers and Electro-Optics Society, 2006.

[7] Duvillaret L. et al., ”Electro-optic sensors for electric field measurements. II. Choice of the crystals and complete optimization of Their orientation”, J. Opt. Soc. Am. B 19, p 2704-2715 (2002)

[8] K. Bohnert, P. Gabus, J. Kostovic, H. Brndle, ”Optical fiber sensors for the electric power industry”, Optics and Lasers in Engineering, 2005.

[9] ”Current Developments in Optical Fiber Technology”, book edited by Sulaiman Wadi Harun and Hamzah Arof, ISBN 978-953-51-1148-1, 2013.

[10] Huang, S.J.; Erickson, Dennis C., ”The Potential Use of Optical Sensors for the Measurement of Electric Field Distribution,” in Power Engineering Review, 1989.

[11] Kuehn, S.; Bomholt, F.; Kuster, N., ”Miniature electro-optical probe for magnitude, phase and time-domain measurements of radio-frequency magnetic fields,” in Electromagnetic Compatibility (APEMC), 2010.

[12] Murooka, Y. Nakano, T. Takahashi, Y. Kawakami, T., ”Modified Pockels sensor for electric-field measurements,” in Science, Measurement and Technology, 1994.

[13] Yang Yongjun, Chen Fushen, ”Optical Characteristics of the Optical E-Field Sensor Using LiNbO3 M-Z Waveguides in the Static Field,” in Communications, Circuits and Systems Proceedings, 2006.

[14] Loader B, Gregory, A.; Bownds, D.; Seifert, F., ”Evaluation of an optical electric field sensor for measurement of specific absorption rate (SAR) during magnetic resonance imaging,” in Electromagnetic Compatibility (EMC EUROPE), 2012.

[15] Duvillaret. Lionel, (Dec. 2015), ”Les bons critres de mesure en lectromagntisme”. [Online]. Available: http://www.kapteos.com

[16] E. Grudzinski, V. Nichoga, I. Prudyus, ”Antennas in Metrology of Electromagnetic Fields near Radiation Sources”, 2007.

[17] K.M. Abramski, H. trzaska, ”FM EMF Sensors”, Technical University of Wroclaw, 2002.

[18] Market Research Report - 245023 Fiber Optic Sensors Market Forecast (February 2015)

[19] Mohamad Yasin, Sulaiman Wadi Harun and Hamzah Arof, ”Optical Sensors - New Developments and Practical Applications”, book edited, 2014.

[20] Anguera Jaume, Antonio Prez, ”Teora de antenas”, Universitat Ramon Llull, 2008.

[21] Pramod K. Rastogi, ”Optical Measurement Techniques and Applications”, Artech House, 1997.

[22] Jackson D.A, ”Elimination of Drift in a Single-Mode Optical Fiber Interferometer Using a Piezoelectrically Streteched Colied Fiber ”, appl. Optics, Vol 19, 1980.

[23] Cole, J. H., ”Synthetic Heterodyne Interferometric Demodulation”, J. Quand. Electron, Vol 18, 1982.

[24] Kersey A.D., ”Phase Compensation Scheme Suitable for Use in Single Mode Fiber Interferometer”, Electron lett, Vol 18, 1982.

[25] Dandridge, A., ”Homodyne Demodulation Scheme for Fiber-Optic Sensors Using Phase Generated Carrier”, J. Quand. Electron, Vol 18, 1982.

[26] Lee, C.E., H.F. Taylor, ”Interferometric Optical Fiber Sensors Using Internal Mirrors”, Electron lett, Vol 24, 1988.

[27] Lee, C.E., ”In-Line Fiber Fabry-Perot Interferometer with High Reflectance Internal Mirrors”, 8th Int. Conf. Optical Fiber Sensors, Monterey, CA, 1992.

[28] Murphy, K.A., ”Extrinsic Fabry-Perot Optical Fiber Sensor”, 8th Int. Conf. Optical Fiber Sensors, Monterey, CA, 1992.

[29] Culshaw B., ”Fiber-Optic Sensing: A Historical Perspective”. J. Lightwave Technol, 2008

[30] J. Kausche, G. Mielke, ”EMF Measurement on LTE signals using the RS-TS EMF portable system”, Rhode-schwarz systems.

[31] Udd E, Spillman Jr WB, ”Fiber Optic Sensors: An Introduction for Engineers and Scientists”, Vol 2, New York, USA, 2011.

[32] U. Sharma, X. Wei, ”Fiber Optic Interferomtric Devices”, Carl Zeiss Meditec, Inc., 2013.

[33] Sirkis, J. et al., ”In-Line Fiber Etalon (ILFE) Fiber Optic Strain Sensor”, J. Lightwave Tech., Vol 13, 1995.

[34] Koo, K.P., G.H. Sigel ”A Fiber Optic Magnetic Gradiometer”, J. Lightwave Tech., Vol 1, 1983.

[35] Vorha S.T., ”DC and Low Frequency Fiber Optic Electric Field Sensor ”, Optics lett, Vol 16, 1991.