PHOTONICS FOR SAFETY AND SECURITY

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PHOTONICS
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One of the authors wants to dedicate this book to his women:
Maria Alessandra, Maria Teresa and Emilia, and to his parents (AC)

To Penny, who will always live in my heart (AT)

Preface

The tremendous amount of technology available today would allow us to guarantee the perfect safety and security of any site with reliability very close to 100%. This dream might be realized under two extreme conditions:

- no budget limitation has to be taken into account,
- no legal constrains would limit the technological choices.

In everyday life the above mentioned constrains would strongly restrict the choices effectively available. An example over all is the terahertz technology. It might offer the possibility of the perfect scan of any person in order to easily discover the presence of explosives, drugs and also non metallic weapons.

Anyhow, one of the major challenges of this technology is just its power and its capability of performing the accurate scan of any body. In fact, each person would appear completely naked thus showing any personal defect or anomaly. This is a typical case in which the possibility offered by technology is strongly limited by the natural need of privacy.

Another case very similar to this is offered by the possibility of registering the main identifying elements of each person passing through an assigned gate. Many of us, entering the United States or many Middle East countries, have been scanned in the eye, pictured and have had their finger prints registered. This approach is totally forbidden in many European countries.

In addition, we observe that, as each physical quantity can be measured in many different ways, the final choice is not only a matter of price or performance but very often is limited by the boundary conditions of the measurement. As an example, we can refer to very high temperature measurements, which can be made only by infrared detectors. Of course, no sensor or no measurement method can be the jolly of any practical situation.

With the previous considerations in mind a modern sensor engineer would be able to design a safety and/or security system with the classical goal of maximizing its performance for a given total available budget. This means that this kind of engineer must know the basic characteristics of any sensor in order to integrate it according to the specific requirements.

Why photonics?

Photonics is a remarkable technological field able to support a multi-billion Euros per year market.

It is essentially based on the photons – matter interaction. It plays a fundamental role in safety and security because of its capability to supply sensors which can be sensitive only to a specific parameter being totally insensitive to any other agent. A specific example is offered just by optical fiber sensors which, unless specific tools are intentionally used, are characterized by a total independence of any other environmental parameter. Free space propagation, on the other side, is the fundamental tool for a variety of contactless and not invasive diagnostic techniques. Indeed, this last property is shared with all measurement techniques based on the use of waves, either acoustic or electromagnetic.

Today, based on the use of extremely miniaturized devices, photonics is able to supply compact and user friendly systems easy to be embedded almost in any apparatus. In addition, the possibility to separate the diagnostic sensor from the electrical apparatus makes photonic devices ideal candidates in many dangerous or extreme environments likes explosive substances tanks, low or high temperature environment, high electromagnetic field systems. It is enough to think about measurements to be performed inside cryogenic environments where the optical fiber is often the only suitable candidate, or high temperature furnaces for semiconductor processing where light is the unique possibility for real time online measurements. And also explosive or flammable substance pipes, tanks where any parameter measurements must provide the total absence of any electrical signal.

Besides the previous cases, another field of interest is that of medical and food application where the perfect chemical inertial properties of the glass play a fundamental role for using optical fibers for a large variety of different measurements.

In this volume, the authors aim to give a survey of the wide range of applications of photonics in the fascinating field of safety and security. The book continues the series initiated with the Handbook *An Introduction to Optoelectronic Sensors*, containing the state-of-the-art of optoelectronic technologies for sensing.

Photonics for Safety and Security is a collection of up-to-date contributions by renowned experts in the field. After a chapter introducing the principal concepts which underpin the realization of photonic systems, a large variety of photonics applications in different areas of safety and security is illustrated.

The overview of the different applications ranges from the use of Fiber Bragg Grating sensors for diagnostic and control in civil structures, remote sensing techniques for earth and territory monitoring, cultural heritage, food industry, detection of chemicals, drugs and explosives, environment, underwater monitoring, aerospace devices, medical and clinical diagnostics, quantum cryptography, night vision and many others such as the ever so popular forensic sciences.

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WHAT IS PHOTONICS?

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This chapter outlines in brief the principal concepts which underpin the realization of photonic systems. The aim in a few pages is to present a qualitative introduction supported by a bibliography which will hopefully enable the reader to seek more quantitative information and additional conceptual depth.

1. Introduction

Photonics, like many generic technical terms, has yet to be blessed with an unambiguous definition. Sometime during the last few decades the combination of the word "photon" and the word "electronics" emerged to describe science, art and technology of appreciating and utilizing that part of the electromagnetic spectrum which manifests itself predominately as photons rather than predominately as electric currents or magnetic fields; loosely, indeed very loosely defined as "working with light". We could attempt to be more precise. If an electromagnetic wave is to appear in some form of detection circuit as a particle rather than an induced current, then intuitively the energy of that particle must comfortably exceed the thermal energy of the particles within the detector. In this context the detector can be a photodiode, a photographic emulsion, a CCD array or even your eye. All will respond to photons.

Continuing this argument and observing that the photon energy for electromagnetic radiation at 1 μm in the near infra-red is about 1.2 eV and the equivalent thermal energy at 300 K is about 0.025 eV then – very roughly – anything that deals with electromagnetic radiation of wavelength less than around 5 μm can be considered to be "photonics".

This, of course, leads into a somewhat paradoxical world.

Electromagnetic radiation is still electromagnetic radiation so everything about waves still applies. The wave concept[1] is extremely useful, even indispensable, when looking at propagation through media with dimensions much larger than the wavelength. Indeed it still applies at dimensions comparable to a wavelength where all the well known wave guiding and diffraction ideas can be reliably brought to bear.

It is only then at the detection process – when this electromagnetic radiation interacts with a material – that the photon comes into its own.

This, of course, covers a huge range of well known phenomena, not only photodetectors themselves but everything to do with spectroscopy and even concepts like radiation pressure, photothermal phenomena and non-linear scattering. The "photonics" label embraces other nuance as well. If we make things small enough - much smaller than the wavelength - then instead of wave phenomena or even molecular properties determining what happens to the electromagnetic wave, we can begin to exploit the concepts of electronic circuits leading into nanophotonics[2] leading to even more esoteric ideas, like negative index materials, using a slight modifications to all the conceptual underpinning which circuit designers have been using for decades without ever appreciating this alternative perspective.

So the aim of this short chapter is to very briefly introduce the concepts (figure 1) behind the generation, detection and manipulation of electromagnetic signals in the photonic region of the spectrum.

2. Photons – Waves or Particles?

Weighty volumes[3] have been written on this with no real conclusion apart from that it is all a matter of convenience. Detection and generation in the photonic region of the spectrum is a photon based affair and is treated as such, though as nanophotonics gains ground perhaps circuit based generation concepts will emerge. Indeed, with suitably tight structural tolerances, the concepts of the microwave travelling wave[4] tube could easily be scaled up in frequency though whether this might be valuable is an entirely different question. Similarly the concepts of the interaction between electromagnetic radiation in this part of the spectrum and materials are also more simply viewed in the photon domain[5].

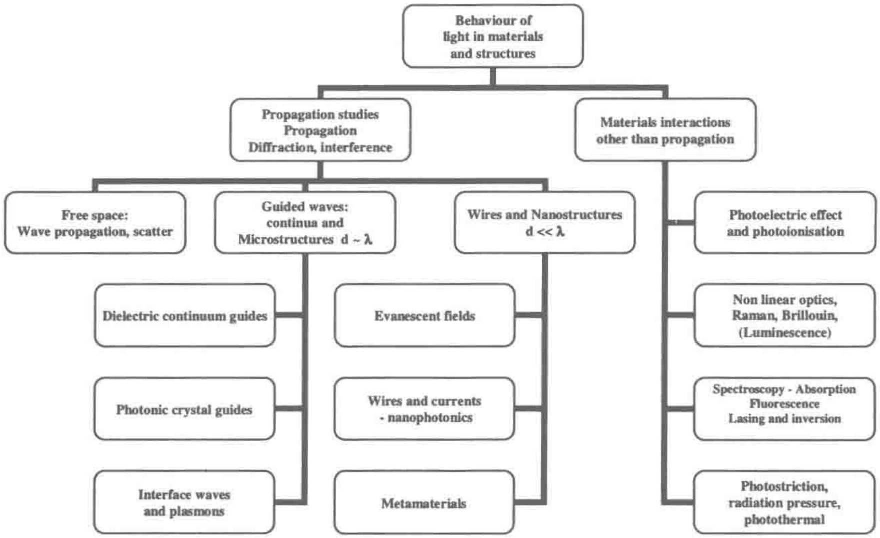

Fig. 1. What is Photonics? This illustrates the principal concepts.

However, when it comes to propagation and the interaction with structures rather than materials, then provided that the structural features are much larger than or comparable to a wavelength then the ideas of waves principally diffraction, interference and polarization are all that is required.

This works fine when the total energy in the system we are considering corresponds to lots and lots and lots of photons. It gets a little shakier when very few photons are involved, or does it? Long ago, the idea that, for example, an interference pattern is really an expression of a photon arrival probability distribution[6] emerged and became philosophically accepted. Consequently the idea of "lots and lots" of photons corresponds to having enough (hundreds, preferably thousands) to plot out the distribution. With few photons around, the ideas of "entanglement"[7] lead into apparently more and more mysterious phenomena. However, for many, perhaps all, of the situations where this mystery prevails, thinking of the generation and detection process as photons and the propagation in-between as waves, goes a long way to intuitively grasping what it is really all about.

3. Manipulating Photons: Structures and Materials

The basic phenomena are essentially determined by the dimensions of the structure compared to the wavelength of the propagating (or even entrapped) radiation.

For very large structures much greater than a wavelength in dimension free space propagation prevails and it is here that the concept of the refractive index or dielectric constant is arguably the most important contribution. What is particularly important is that the photonic region of the spectrum by definition includes frequencies at which the molecules of the material itself are resonant – they absorb. The classical simplistic treatment of the dielectric constant through the Clausius Mosotti[8] equation, which also emerges more or less unscathed from a quantum mechanical treatment, gives behavior typified by the sketch in figure 2. The rapid variations in index at particular frequencies are an inevitable consequence of the resonances and these clearly introduce dispersion and can even when tuned and tweaked to be reinvented as "slow" light[9].

So fundamentally the refractive index invariably has considerable structure within it. This inevitably reflects into the material's propagation properties and indeed the features within it which can be exploited. Moreover, a truly homogeneous medium is at best elusive and perhaps impossible to realize so there will be variations in density and consequently index throughout the material often over very small dimensions. These variations also make their mark and manifest themselves as scatter[10], an effect which gives us our blue skies and also our white clouds, but which can also be invaluable as a measurement tool, for example, to detect size the distribution of particles in air or of tiny creatures in water[11]. When the features become comparable to the wavelength then we encounter two very important domains of photonics both of which implicitly exploit diffraction and interference.