Materials R&D as enablers for quantum leaps in photonics device development and performance

Lars Thylén[a,b,c]
[a]Dept of Microelectronics and Applied Physics, Royal Institute of Technology (KTH) Stockholm, Sweden
[b]Kista Photonics Research Center, Stockholm, Sweden
[c]Joint Research Center of Photonics of the Royal Institute of Technology and Zhejiang University, Hangzhou, PR China

ABSTRACT

Progress in photonics and indeed in many areas of science and technology has in many cases been closely linked to development in materials. This development has in some cases been initiated by theoretical considerations and requirements formulation, in other cases novel materials have opened up unexpected applications. Examples of the former are given, where materials meeting certain requirements would lead to quantum leaps in device performance.

Keywords: optical materials, photonics materials.

1. INTRODUCTION

Technology development has over the past several decades shown an ever increasing pace. Photonics is no exception here and the progress can be broadly subdivided in engineering improvements (very necessary) with the aim of increasing performance/cost; research and development at various levels and blue sky research without any specific goals. In many cases (all?) it is the last one which has supplied the real impact, natural since it has unveiled the unknown. Milestones in photonics have been the discovery of the photon and the understanding of the photon matter interactions to a very detailed level. At a less fundamental level we have the hereto structure laser diode and related structures, the optical fiber and erbium amplifiers. Regarding the optical fiber, formulated systems requirement (Kao et al) led to intensive efforts to develop the material and technology to make glass with a transparency unheard of. At the same time there are currently several barriers left in photonics, such as imaging resolution as well as size and functionality of devices to name just a few. Integrated photonics, a concept invented in the 70s concurrent with the emerging tremendous impact of the electronic IC was (mistakenly) taken for an analog and parallel to this development, and only recently have we seen something similar transpiring in integrated photonics.

This paper treats some aspects where materials, were they available in an efficient way, would have a large impact. But these are just examples, the field of materials science in photonics and its more and more active combination with life sciences is a huge one.

2. SOME SAMPLE MATERIALS ISSUES IN PHOTONICS

2.1 Negative index materials

Following the pioneering theoretical study by Veselago in the 60s, not much happened until the issue was again recently brought up, and an intensive research is today carried out regarding negative index materials, or to be more precise, materials that have a negative ε as well as μ. Such materials must be strongly dispersive (and hence lossy) as given by the equation for the energy density. Negative ε can be found in metals, as discussed below, but negative μ is a more difficult option. However, "metamaterials" have been created where a combination of micro rods and ring resonators actually do generate negative ε as well as μ. This is (independent of losses incurred by the dispersion of these media)

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accompanied by the loss created by the metals, at room temperature, i e the same problem as mentioned below. The interest in negative index material is partly due to the possibility if beating the Rayleigh limit, and maybe perform tasks such as imaging at molecular level, but there are also interesting issues such as reverse Doppler effect. A break through here awaits low optical loss materials with ε as well as μ negative in the optical frequency region., something that is yet to be developed or discovered.

2.2 Photonic crystals

Photonic crystals (PhCs) are structures periodic in 1, 2 or 3 dimensions, with a period on the order of the light wavelength. Research in PhCs has more or less exploded over the past several years, fuelled by the expectations of dramatic improvements in photonics device performance, especially regarding functionality, size and eventually cost. An example of the improvements in size that can be achieved is given by point defect resonators, as opposed to existing ring and pillbox resonators; however, the optical losses are still high and the loss issue continues to be a problem for PhC applications. Although superficially the prevalent 2D or 3D PhCs could be regarded as just extrapolations of the well known 1D Bragg gratings, it turns out that there is a wealth of phenomena and possibilities when increasing the number of dimensions from 1 to 2 and 3, with an immense potential, still to be explored.

It has to be recognized that PhCs are not better at confining light in waveguides, as compared to ordinary waveguides (but are superior for point defect resonators) and that the issue of polarization dependence is in general aggravated in PhC based circuits. However, PhCs allow the unique features of dispersion engineering (group and phase velocity and the possibility of a bandgap) and sample applications cover a broad spectrum: Compact modulators and filters, heterostructure devices, storage of light in point defects, optical logic due to nonlinearities, efficient LEDs and lasers, dispersion compensation, A/D converters, negative refractive index devices, superprism effects. For current research and for more near term applications, a structure where the periodicity is in 2D and the light confinement in the 3rd dimension is accomplished by a refractive index step, as in conventional waveguides is dominating. The materials issues in PhCs concern precision and ease of fabrication, where the requirements in some cases are daunting. As for 3 D periodic structures, one additional problem is the controlled introduction of point and line defects.

2.3 Plasmonics

As mentioned above, the photonic crystals do not per se resolve all the issues of the size of photonics devices in relation to electronics: an optical waveguide is on the order of a micron in width, and optical devices are at the very best on the same order in length, as compared to several 10s of nm for FETs. Efforts to explain the sheer physical size difference by the wide gap between the electron de Broglie wavelength and the optical wavelength are fairly futile since the scaling of electronic devices does not involve, at least not currently, wave based devices.

A possible solution here is different types of plasmon structures. Plasmons are collective excitations in charge carrier gases, as induced by electromagnetic fields. The optical waveguide transverse dimensions can be made arbitrarily small, as is also the case for the resonator size, however, at present, at the expense of eventually extremely large losses. In essence, the feasibility of more complex plasmon circuits is more of a solid-state physics problem than anything else: That of reducing “friction” losses in charge carrier gases (or equivalent materials), a very challenging research field indeed. The problems are similar to those of section 2.1, although simplified in that only ε has to be negative with low loss.

It should be noted that some applications here, such as 3 dB splitters, which are very short, fractions of a wavelength, can be implemented with current metals, at room temperature, however, other applications such as resonators suffer from the loss. Quantifying of the required decrease in material loss has been made.

2.4 Coherent light matter interactions

Coherent interactions between light and matter such as stimulated emission; self-induced transparency and Rabi oscillations have been studied in atomic physics at least since the discovery of the Hanle effect. Most coherent effects are *native* properties of the atoms and hard to modify. It is however very desirable to coherently control photons and matter since it would potentially have many applications and allow more precise studies of quantum systems. For instance, the concept of quantum computing is based on the idea of coherent manipulation of qubits. One example of coherent interactions is electromagnetically induced transparency (EIT). For the prevalently used 3 level system a number of applications have been suggested and partly demonstrated, such as optical pulse storage and read out, pulse compression, fast gating, pulse train generation, parallel to serial conversion, wavelength conversion, spatial switching, filtering, multiplexing.

The main reason why EIT is so useful is that it is possible to use one light field to control the dynamics of another light field. The mechanism provides a new set of control *parameters*, such as the wavelength and intensity of the controlling light field. Also, it is possible to design quantum well systems where one can electronically tune the control parameters. via dipole matrix elements and energy separations between the active levels forming the so called Λ system needed for EIT. This makes it possible to use EIT as an efficient interface between optics and electronics. One of the main features of EIT is that it allows nearly full control of the group velocity for light pulses. Experimentally, light has been completely halted and the stored light was subsequently read out again. This aspect may be used to control the propagation direction of a light pulse. The main issue here is to find suitable material systems where the coherence times exceeds the time needed for manipulation of the optical pulses. This is so, since the EIT operation relies on mutual coherence between two or more states in an atom or a quantum dot or in general the system used. The most interesting structures, quantum dots, unfortunately show coherence times well below 1 ps (at room temperature); whereas the less versatile atoms can reach several ms. These are again very challenging materials issues.

2.5 Biophotonics

This is again a rapidly growing field, and one where photonics can be used for imaging, diagnosis and therapy. But biotech could also be used for fabrication of photonics structures, something that has been discussed for along time, but with few results. Especially in the field of PhC, where extreme precision and efficient fabrication are highly desirable, alternatives to the “hammer and sledge” method normally employed would be extremely interesting. Even though 3 D structures of a periodic nature can be fabricated with these novel methods, the mentioned problem with defects introduction persists,

3. SUMMARY AND OUTLOOK

Several examples of current materials issues in photonics have been discussed. The perspective has been one of formulating requirements on materials, but it is also clear that, materials research in its own right to reveal the unexpected is very important. While in electronics silicon has kept its position for half a century, photonics relies on a broad range of materials, fabrication technologies and devices structures. While the last one is probably unavoidable with the enormous scope of applications, the diversity in materials tends to make photonics technology costly.

Regarding some of the fields treated above, it appears that wave function engineering would supply a solution. This is indeed a challenge.