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Review Article

A Qualitative Review of the Theoretical Formulation and some Experimental Advances in Meta materials for Novel Opto-Electronic Devices Useful in Aeronautics Industry

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ABSTRACT

The present paper is a serious effort in providing an extensive technical analysis and overview of the recent theoretical and experimental advances in metamaterials. The paper deals with the analytical treatment, conceptual explanation and unique characteristics of artificial dielectrics in the form of photonic crystals. A qualitative review of the available experimental results for better understanding of the concepts has been given. The technical analysis of the theoretical aspects of concepts and characterization of the dielectric materials in the form of photonic crystals, their band structure, and devices based on them, with emphasis on designing of fibers, and novel lasers with nanostructures, and plasmonic photonic crystals along with the modeling and designing considerations for maximizing the efficiency of some of such devices, has been done very briefly in order to give a comprehensive picture about the various aspects of such materials. Their role as hydrogel sensors in medicine and biosensors has also been briefly mentioned. This paper is expected to be immensely useful for the researchers and designers in this novel evolving field, and also in choosing a direction for their research work on artificial dielectric materials.

Keywords: Dual-band metamaterial absorbers; Spatial light modulators; Dielectric materials based hydrogel sensors

INTRODUCTION

Novel concepts of artificial dielectrics in the form of photonic crystals

Foteinopoulou [1] has very well explained that, the realization of man-made structures with unprecedented electromagnetic (EM) properties are known as metamaterials, which are typically periodic metallic-based resonant structures demonstrating effective constitutive parameters beyond the possibilities of natural materials e.g., they can exhibit optical magnetism or simultaneously negative effective permeability and permittivity implying the existence of a negative refractive index. Also periodic dielectric and polar materials, known as photonic crystals, can exhibit EM capabilities beyond natural materials. Hence, the photonic crystals can just be considered ss metamaterials. Hence, this paper provides the concepts and applications of artificial dielectrics in the form of photonic crystals (PhCs) are novel optical media in the form of the natural or artificial structures with periodic modulation of the refractive index, which have some strange properties leading to their utility for a number of applications. They have different geometrical structures and are classified into three main categories: one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structures.

Localized modes induced by structural defects

The formation of the localized modes induced by structural defects has been discussed by Dai [2]. As explained in this paper, there are no propagating (real k) modes inside the band gap. However, for the case of the complex wave vector e.g.,$k = k_0 + i\kappa$, the master equation given by $\nabla \times (1/\varepsilon(r)) \times H(r) = (\omega / c)^2 H(r)$.

In this expression, H is the magnetic field, r is the position, omega is the frequency, c is the velocity of the EM wave, and Epsilon is the permittivity.

LITERATURE REVIEW

Del is an operator used in mathematics, in particular in vector calculus, as a vector differential operator, usually represented by the symbol del.

When applied to a function defined on a one-dimensional domain, it denotes its standard derivative as defined in calculus. This upside-down capital delta symbol del, also called "nabla" is used

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to denote the gradient. Del is an operator used in mathematics, in particular in vector calculus, as a vector differential operator, usually represented by the symbol upside-down capital delta.

When applied to a function defined on a one-dimensional domain, it denotes its standard derivative as defined in calculus.

The equation for the case of the magnetic field only, has evanescent modes, i.e.,

$$H(x) = e^{ikx}u(x) = e^{ik_0x}u(x)e^{-\kappa x} \quad (1),$$

which is decaying exponentially. The origination of the complex wave vector has been explained on the basis of its existence in the vicinity of the band. In this equation, k is the complex wave vector and u(x) is the initial amplitude. Here, Delta is the grating element, and Lambda is the wavelength.

Here, Delta is the grating element, and Lambda is the wavelength (Actually delta (Δ) is at most time's means "change" or "the change" in maths.).

As discussed by Dai [2], the upper band near the gap can be approximated by expanding $\omega_2(k)$ in powers of about the zone boundary $k = \pi / a$. It is clear that due to the time-reversal symmetry, the expansion cannot contain odd powers of k, and so the equation for the lowest order can be expressed as:

$$\Delta\omega = \omega_2(k) - \omega_2(\pi / a) = \alpha(k - \pi / a)^2 = \alpha(\Delta k)^2 \quad (2).$$

So, it is observed that for frequencies lower than the top of the gap, i.e., within the gap, $\Delta\omega < 0, \Delta k = i\kappa$ is purely imaginary. Clearly, on traversing the gap, the decay constant κ grows initially as the frequency reaches the mid-gap, and subsequently disappears at the gap edges. In case of the perfect photonic crystals, because of the translational symmetry, the evanescent modes cannot be excited.

Subwavelength PC gratings

A common PC structure consists of periodically modulated thin films, called 1-D slabs, and these structures are generally fabricated from a high refractive index coating layer over a periodically arranged low refractive index grating layer. Interestingly, in these PC gratings, only the zeroth order mode is allowed, while higher order modes are restricted at normal incidence, if the period of the grating (Δ) is chosen to be smaller than the wavelength of the incident light ($\Delta < \lambda$). Hence, these gratings are also called sub wavelength gratings, and exhibit efficient optical resonances [3]. Here, Delta is the grating element, and Lambda is the wavelength. Here, Delta is the grating element, and Lambda is the wavelength (Actually delta (Δ) is at most time's means "change" or "the change" in maths.).

Use of optical resonances for reducing the speed of light

In research work, in some cases, the speed of light has to be reduced. The method for doing that is based on the control of photon propagation in coherently driven three-level atomic media by using atomic resonances, or by using electromagnetically induced transparency [4,5].

Devices based on artificial dielectrics in the form of photonic crystals

Some of the important devices based on artificial dielectrics in the form of photonic crystals have been discussed below:

Light coupling and beam splitting in low refractive-index slab waveguide: It is now well understood that (i) the Coupling between free space components and slab waveguides is a common requirement for integrated optical devices, and is typically achieved by end-fire or grating coupling; (ii) the Power splitting and distribution requires additional components; and (iii) usually grating couplers are used in combination with MMI/Y-splitters to do this task. Shi, et al. [6] have presented a photonic crystal device which performs both tasks simultaneously and is able to couple light at normal incidence and near normal incidence, and have stated that their approach is scalable to large channel counts with little impact on device footprint.

Graphene micro-heaters on silicon photonic crystal waveguides: Slow light has ability to promote light–matter interactions, and therefore, has been widely utilized to obtain enhanced nonlinearities, enhanced spontaneous emissions and increased phase shifts. Yan, et al. [7], have used the technique of incorporating a graphene on a slow-light silicon photonic crystal waveguide, and have experimentally demonstrated an energy-efficient graphene microheater with a tuning efficiency of 1.07 nm mW1 and power consumption per free spectral range of 3.99 mW. They have stated that (i) the rise and decay times (10-90%) are only 750 and 525 ns, which, are the fastest reported response times for microheaters in silicon photonics., and (ii) the corresponding figure of merit of the device is 2.543 nWs, one order of magnitude better than results reported in previous studies. The influence of the length and shape of the graphene heater to the tuning efficiency has also been studied for providing valuable guidelines for enhancing the tuning efficiency of the graphene microheater. Some of the important results of this study have been reproduced shown in below Figure 1.

Architecture for 2D photonic crystal micro-lasers: The band edge micro laser utilizes the unique feedback and memory effects associated with a photonic band edge and stimulated emission (arising from electron-hole recombination) from the multiple quantum well active regions occurs preferentially at the band edge. Defect Mode micro laser requires the engineering of a localized state of light within the 2D PBG. This is created through a missing pore in the 2D photonic crystal. Stimulated emission from the multiple quantum well active regions occurs preferentially into the localized mode. Architecture for 2D photonic crystal micro-lasers has been shown in below Figure 2.

The density of states (ρ) in a large cavity can be approximated as:

$$\rho(\omega) = \frac{1}{\omega_o}\left(\frac{DQ}{V}\right) \quad (3),$$

where ω is the frequency, V is the resonant frequency, V is the volume of the cavity, ω_r is the frequency corresponding to the volume V of the cavity at which $\rho(\omega)$ has the peak value in the lower frequency region, Q is the mode degeneracy, i.e., the number of cavity modes with the same frequency, and Q is the total quality factor. Cavity modes can be coupled to emitters enhancing their spontaneous emission rate. The degree of enhancement is given by the Purcell factor F, as given below [8]:

$$F = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V} \quad (4)$$

Where Q is the total quality factor, λ is the resonant wavelength, and n is the refractive index.

Optical computing: With the availability of the optical integrated circuits and optical transistor technology based on the use of the photonic crystals, quantum computing with localized light is considered as a promising technology for the future applications in the field, since it has many advantages like immense parallelism, unprecedented speeds, superior storage density, minimal crosstalk and interference.

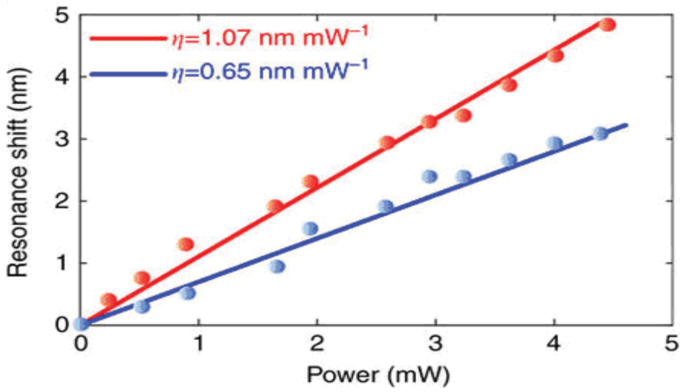

Figure 1: Measured resonance shifts for the interference dips at 1525.12 nm (blue) and 1533.71 nm (red) as functions of the applied heating power.

Optical integrated circuits: Optical integrated circuits are fabricated by using 3-D PBG crystals as the buildings blocks (Figure 3). The buildings blocks (the blue balls) show a metallo-dielectric structure; the green "forests" show 2D periodic photonic crystals and the red "roads" with holes in them display 1D periodic crystal (Figure 3).

Colloidal photonic crystals with nanoparticles with tunable structural colors: Lai and Wang [9] have discussed that polystyrene (PS) colloidal photonic crystals (CPhCs) containing silver nanoparticles (AgNPs) present tunable structural colors. The PS CPhC color films containing a high concentration of AgNPs for their study are prepared by using self-assembly process through gravitational sedimentation method, and the high-concentration AgNPs are deposited on the bottom of the substrate and act as black materials to absorb background and scattering light. It has been claimed that the brilliant structural colors are enhanced because of the absorption of incoherent scattering light, and color saturation is increased by the distribution AgNPs on the

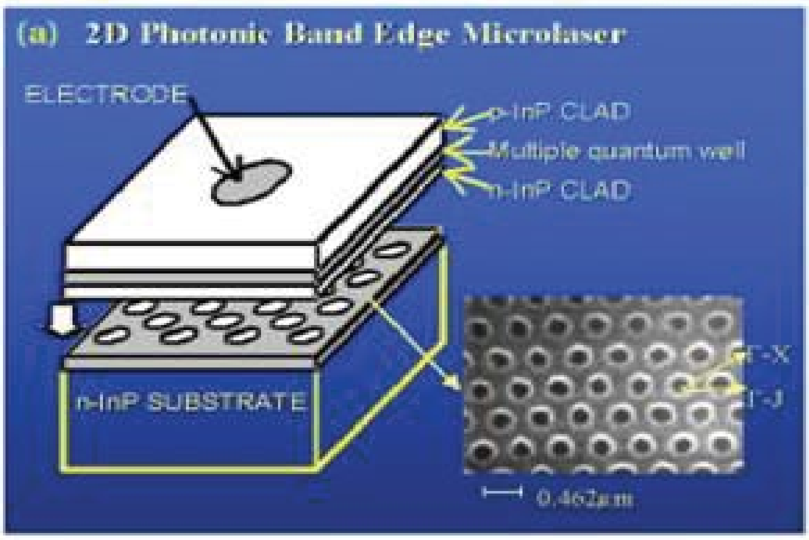

Figure 2: Architecture for 2D photonic crystal micro-lasers. **Figure courtesy:** Scherer Axel, California Institute of Technology.

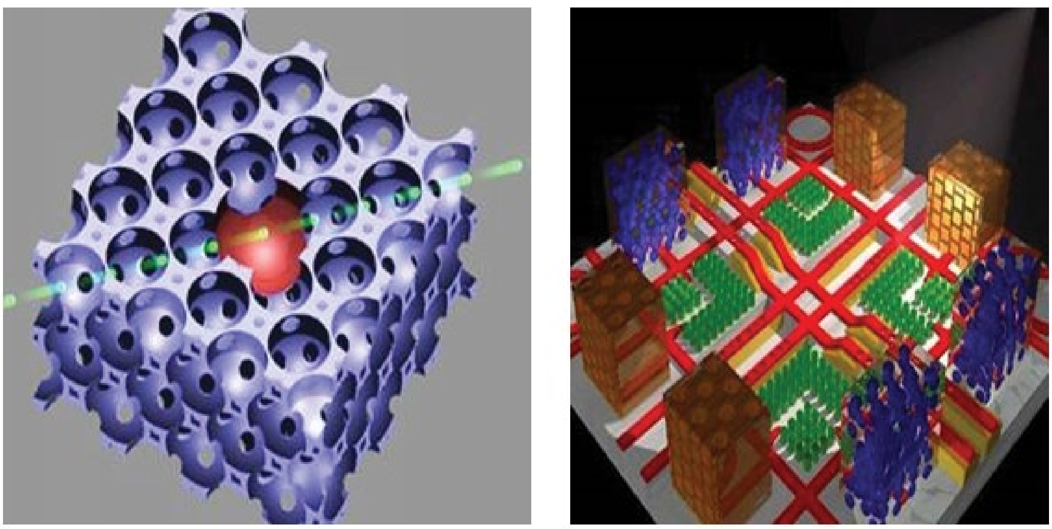

Figure 3: Schematic of optical computing (Left). **Figure courtesy:** Balasubramanian Srivatsan, Rensselaer. Schematic of a collage of different photonic crystal devices going into an integrated circuit (Right).

PS CPhC surfaces. It has been explained that the vivid iridescent structural colors of AgNPs/PS hybrid CPhC films are based on bragg diffraction and backward scattering absorption using AgNPs. Lai and Wang [9] have (i) measured the photonic stop band of PS CPhCs and AgNPs/PS hybrid CPhCs by UV–visible reflection spectrometry and calculated based on the Bragg–Snell law, and (ii) evaluated the tunable structural colors of AgNPs/PS hybrid CPhC films by using color measurements according to the commission international d'Eclairage standard colorimetric system. It has been concluded that this work presents a simple and inexpensive method to produce tunable structural colors for numerous applications, such as textile fabrics, bionic colors, catalysis, and paints. Some of the results of have been reproduced shown in below Figure 4. From all the figures of the transmittance y extinction spectra of AgNPs diluted solutions, it is clear that they almost entirely absorb all wavelengths within the visible region with negligible scattering.

Nanostructures synthesized by photonic crystals liquid-crystal electric tuning of a photonic crystal laser: An interesting property of the photonic crystal (PC) laser is that it can be tuned by changing the orientation of the liquid crystal. An electrically tuned nematic liquid-crystal (LC) infiltrated photonic crystal (PC) laser has been demonstrated, which in fact represents an emerging class of nanoscale optical adaptive devices enabled by the convergence of nonlinear optical materials, electronics, and fluidics that promise increased functionality and utility over existing technologies [10]. It has to be understood that the LC cell is constructed by encasing the PC laser between two indium tin oxide glass plates, which serve as the modulating electrodes. Interestingly, the application of a voltage across the cell realigns the LC, which modifies the laser cavity's optical path length, and thereby blue shifts the lasing wavelength. Very important results for the Spectrum of a photonic crystal nanolaser infiltrated with a liquid crystal tuned by changing the orientation of the liquid crystal have been reported in the

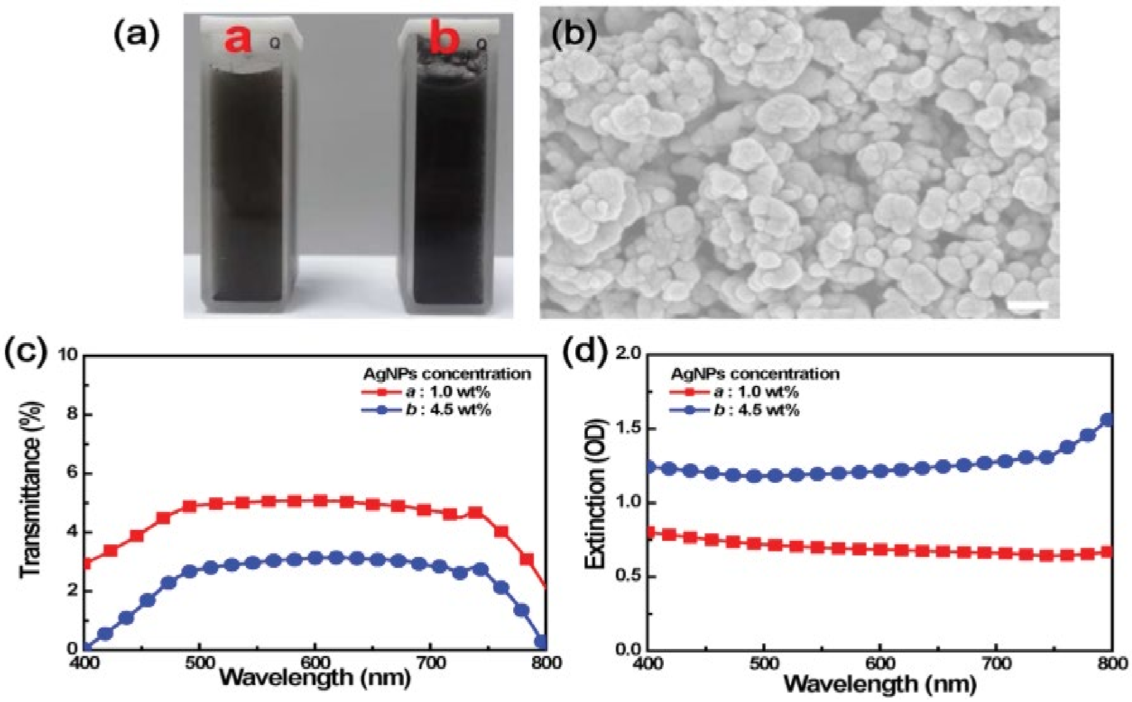

Figure 4: (a) Diluted solution appears black-brown because light is absorbed across the entire visible spectrum. (b) Field-emission scanning electron microscopy (FESEM) image of silver nanoparticle (AgNP) agglomerates at 4.5 wt% concentration. Inset scale bar is 200 nm. (c) Transmittance and (d) Extinction spectra of AgNPs diluted solutions.

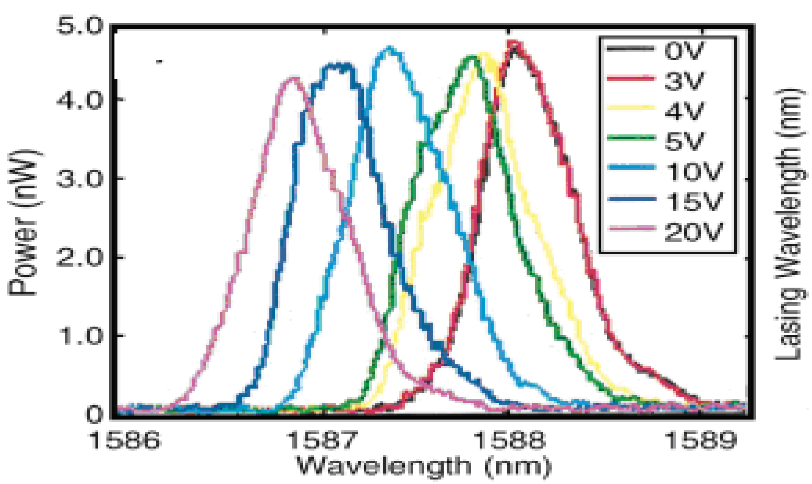

Figure 5: Spectrum of a photonic crystal nanolaser infiltrated with a liquid crystal tuned by changing the orientation of the liquid crystal.

literature, which have been reproduced below [10]. Thus, it is clear that an electrically tuned nematic liquid-crystal (LC) infiltrated photonic crystal (PC) laser has been demonstrated (Figure 5).

Flexible micro/nano lasers and optical curvature sensors on a polymer substrate: It is now known that many microdisk lasers have been demonstrated in a suspended membrane or on the dielectric substrates such as Si/SiO2, III-V and GaN materials, and they work on the flat hard surfaces. However, it has to be appreciated that for future applications like the flexible photonic circuits on human skins, emitters/sensors for bio-systems or optical lasers/sensors on the airplane surfaces, the flexible compact lasers are suitable. The applied nano-photonics laboratory, National Chiao Tung University, Hsinchu, Taiwan [11] has studied a flexible microdisk laser on a polydimethylsiloxane (PDMS) substrate, which has the ability to operate on the non-flat for the desired applications. Clearly, with a flexible platform, such micro/nano-lasers can function not only as a µm size light sources, but also benefit to the flexible laser arrays for the photonic integrated circuits in the non-flat surfaces. Some of the results obtained by the group have been reproduced shown in below Figure 6 [12].

It can be seen that an added advantage of the compact microdisk array is that it can also function as the compact optical curvature sensors with the tunable lasing wavelength.

Designing of plasmonic photonic crystals

The topic of designing of plasmonic photonic crystals, plasmonic photonic crystals, and optical quantum metamaterials has recently drawn the attention of various researchers.

Plasmonic photonic crystals: It is reported that the Localized surface plasmon resonance (LSPR), based on the noble metal nanoparticles, has a great potential in cell imaging photothermal therapy, since these nanoparticles have strong absorption and scattering cross-section at its surface plasmon resonance (SPR) band, which is very sensitive to the various parameters like the local refractive index, size, shape, and chemical compositions of the nanostructures, and therefore, the nanomaterials are being considered for applications in the optical detection of cancer cells. This is a rapid, low cost, and sensitive technique for the clinical diagnosis. The Au or Ag nanoparticles are found to be the most suitable for bio-sensing applications, because they are non-toxic and non-immunotoxic to cells, highly biocompatible, and also have their surface plasmon resonance (SPR) bands within the visible and the NIR regions. A lot of research effort is currently being made on their applications in drug delivery, and cancer cell diagnostics. Au nanoparticles using monolayer of polystyrene

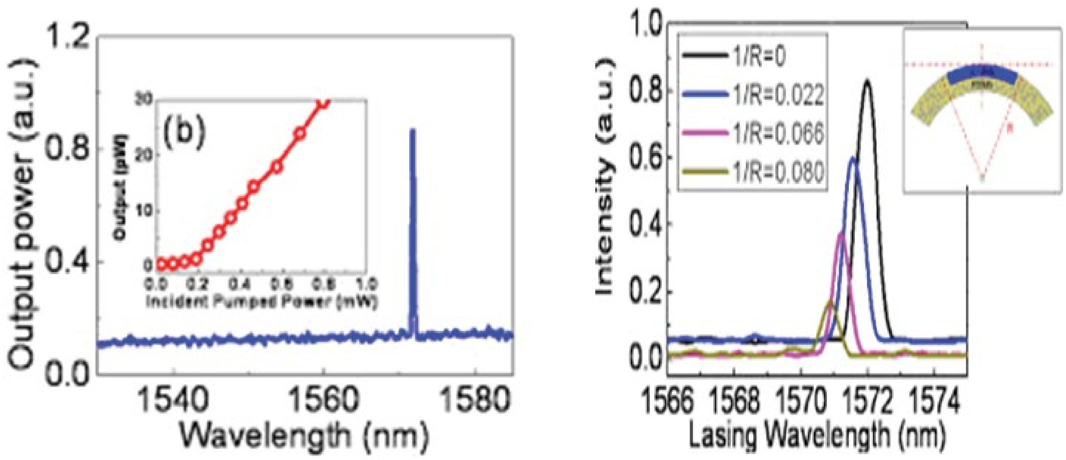

Figure 6: (Left) The lasing spectrum curve of a flexible microdisk laser, and (Right) the curvature sensing properties with tunable lasing wavelength of a bent micro disk cavity.

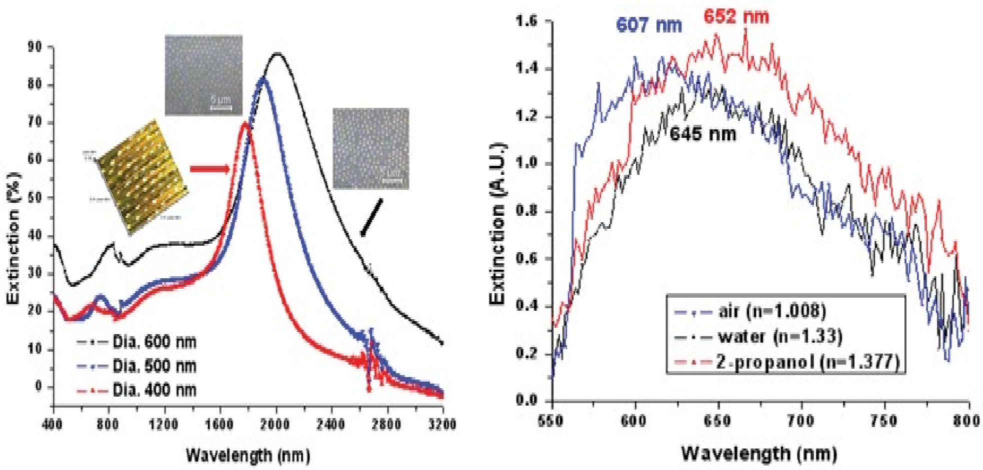

Figure 7: Left graph; Extinction spectra of Au dots with 400 nm, 500 nm, and 600 nm diameter, Right graph; Shift of resonance peaks in different media.

spheres coated on glass have already been designed and fabricated. The extinction spectra of these Au disks and the Shift of resonance peaks as reported in the literature have been reproduced shown in below Figure 7.

As is clear from the figure, LSPR effect is observed, which at present is being tested for detecting biomolecules and cells. The figure shows the extinction spectra of Au dots with 400, 500, and 600 nm diameter, which make it clear that the peak value increases with increase in the diameter of the dots, and also that the resonance shift in different media electromagnetic quantum metamaterials.

The research work on quantum metamaterials in the optical, or near IR, region of the spectrum has recently picked up. The term quantum metamaterial is used in various forms to denote: (i) a structure in which quantum degrees of freedom are inserted, (ii) 'quantum dots metamaterials', which is used to stress that, although quantum dots are inserted in a metamaterial, it is not of interest to know about the quantum coherence of the dots, but the gain provided by them is important, for compensating the losses because of the presence of metallic inclusions, and (iii) quantum wells, which are inserted in a photonic structures, and are described electromagnetically by a permittivity allowing some control over the behavior of the structure. A common layered metamaterial is one, in which the period consists of two GaAs quantum wells, and results in an effective permittivity tensor allowing obtaining a negative refraction. It is important to note that the effective properties on such structures strongly depend upon the 2D electron density in the quantum well. Weick and his group [13-15] have discussed that a collection of metallic nanoparticles exhibits collective plasmonic modes. However, it is important to appreciate that a genuine and useful quantum metamaterial in addition requires the active coherent control of the quantum state of the 'atoms' inserted in the photonic structure, in order to induce a control over the collective properties of the medium. Quach, et al. [16] have introduced the concept of a quantum metamaterial by coupling controllable quantum systems into larger structures, and stated that the conventional metamaterials represent one of the most important frontiers in optical design, with applications in diverse fields ranging from medicine to aerospace. Initially, the metamaterials had been described as classical structures, which interact only with the classical properties of light. Quach, et al. [16] have described a class of dynamic metamaterials, based on the quantum properties of coupled atom-cavity arrays, which are intrinsically lossless, reconfigurable, and operate fundamentally at the quantum level. A cavity array meta-material suggested by Quach, et al. [16], and has been shown in below Figure 8.

The concepts related to Metamaterials like optical resonance for reducing speed of light, artificial dielectrics, optical computing, plasmonic photonic crystal, and optical Integrated circuit.

The concepts related to the topic in this paper like optical resonance for reducing speed of light, artificial dielectrics, optical computing, plasmonic photonic crystal, and optical Integrated circuits, are very important, and have been briefly discussed in this section.

Optical resonance

Optical resonance is used for reducing speed of light: Interest in Slow light has grown since 1999, when the propagation velocity of light could be reduced in an experiment to 17 m/s, i.e., almost 20 million times slower than in vacuum. A couple of years later light pulses could be stopped, or more specifically stored in an atomic medium and subsequently released after some time. These breakthroughs provided the basis for important applications in photon-based quantum information technology.

Artificial dielectrics: Artificial dielectrics are just the fabricated composite materials, and are mostly consisting of arrays of conductive shapes or particles in a nonconductive support matrix, designed to have specific electromagnetic properties similar to those of dielectrics. It is interesting to note that as long as the lattice spacing is smaller than a wavelength, these substances can refract and diffract electromagnetic waves, and are used to make lenses, diffraction gratings, mirrors, and polarizers for microwaves. These unique materials were first conceptualized, constructed and deployed for interaction in the microwave frequency range in the 1940s and 1950s. The constructed medium, the artificial dielectric, has an effective permittivity and effective permeability, as desired.

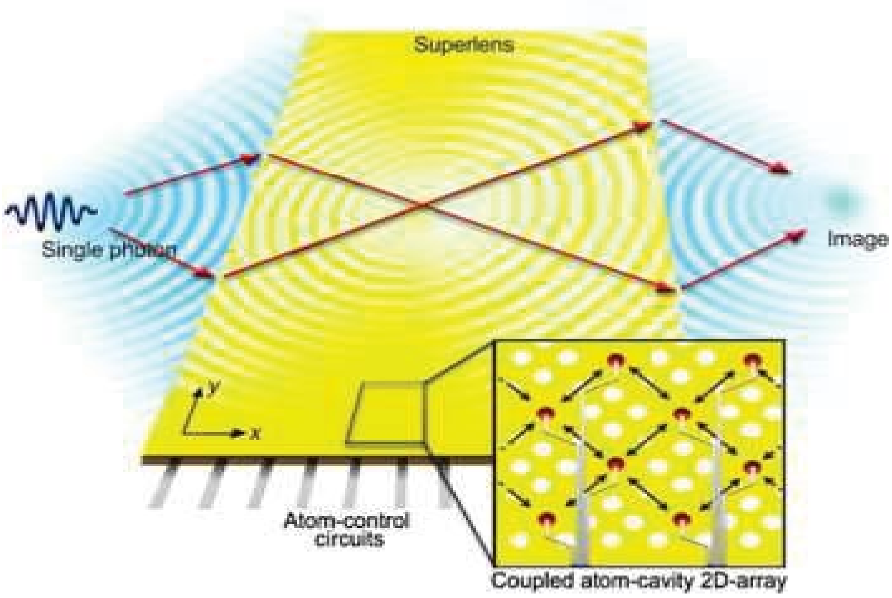

Figure 8: A cavity array meta-material.

Optical or photonic computing: Optical or photonic computing is based on using photons produced by lasers or diodes for computation. This is due to the fact that for decades, photons have promised to allow a higher bandwidth than the electrons used in conventional computers.

Plasmonic photonic crystals: In another interesting development, a dielectric plasmonic photonic crystal for manipulating surface plasmon polariton (SPP) fields can be designed, fabricated, and tested. Interestingly, the band structure of SPP fields inside the plasmonic photonic crystal can be calculated using the plane wave expansion method and validated by full wave numerical simulations.

Photonic integrated circuit or integrated optical circuit: A photonic integrated circuit or integrated optical circuit is an important device that integrates multiple photonic functions, and hence is similar to an electronic integrated circuit.

Applications of photonic crystals in medical field

Wang, et al. [17] have discussed that the hydrogel photonic crystal microparticles (HPCMs) with inverse opal structure can be prepared by a combination of microfluidic and templating technique. The Schematic of the preparation of hydrogel photonic crystal microparticles (HPCMs) with inverse opal structure has been shown in below Figure 9.

Navarra, et al. [18] have made an interesting study of the Cellulose-based hydrogels, obtained by tuned, low-cost synthetic routes, are proposed as convenient gel electrolyte membranes. Interestingly, the hydrogels may be prepared from different types of cellulose by optimizing the solubilization and crosslinking steps, and the gel membranes can be characterized by various characterizing techniques like infrared spectroscopy, scanning electron microscopy, thermogravimetric analysis, and mechanical tests in order to investigate respectively the crosslinking occurrence and modifications of cellulose resulting from the synthetic process, morphology of the hydrogels, their thermal stability, and viscoelastic-extensional properties. The successful applicability of the proposed membranes as gel electrolytes for electrochemical devices can be judged by evaluating the Hydrogels liquid uptake capability and ionic conductivity, based on the absorption of aqueous electrolytic solutions. This can be done by studying the redox behavior of electroactive species entrapped into the hydrogels by cyclic voltammetry tests, which in fact show very high reversibility and ion diffusivity. It is good to note that the hydrogels derived from natural polymers like polysaccharides, are very useful and suitable materials for their applicability in many fields including agriculture, tissue engineering, drug delivery, and biosensors, because of their advantage of being prepared from environmentally-friendly, renewable, and low cost raw materials [19]. It has been established that cellulose combines hydrophilicity with good mechanical properties, which are the competitive characteristics because of the numerous hydroxyl groups, which interact by hydrogen bonds preferentially with water or with

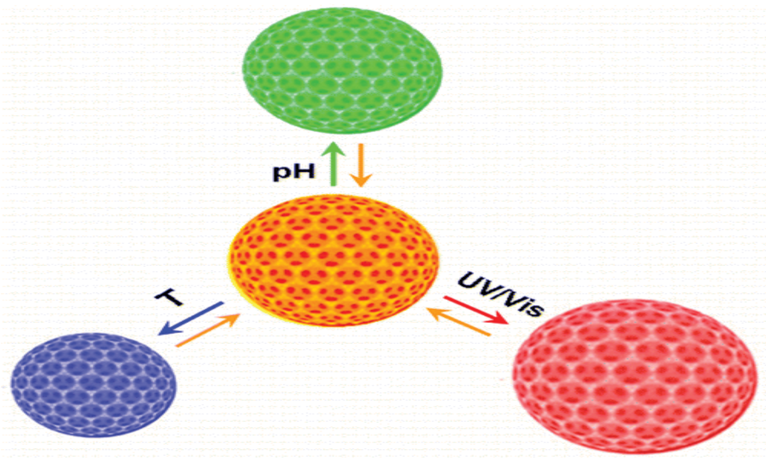

Figure 9: Schematic of the preparation of hydrogel photonic crystal microparticles (HPCMs) with inverse opal structure e.g., N-isopropylacrylamide (NIPAm) and metylacrylic acid (MAA).

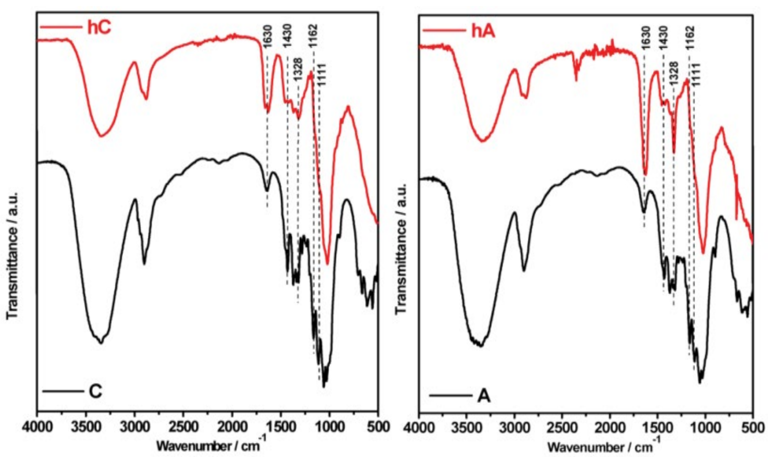

Figure 10: FTIR spectra of the C and A; starting celluloses compared with their hydrogels (hC and hA, respectively).

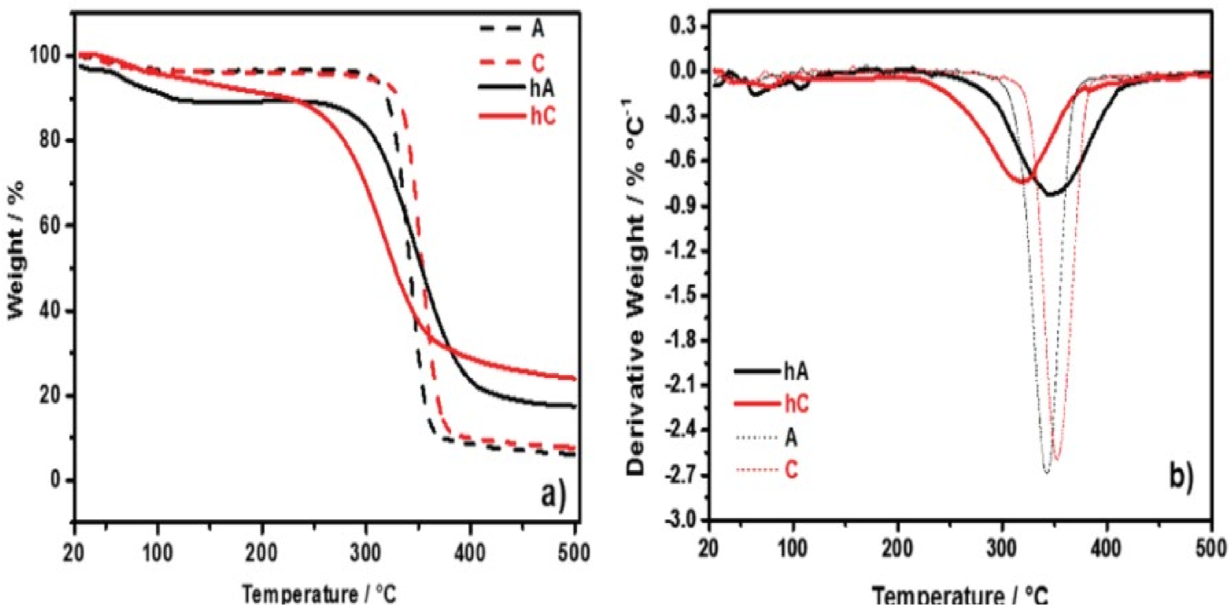

Figure 11: (a) TGA curves of C and A; celluloses, and of their hydrogels (hC and hA, respectively); (b) First derivative of weight curves.

hydroxyl groups of adjacent polymer chains [20]. The results of Navarra et al. as reported in the literature have been reproduced in the Figures 10 and 11 [20].

As expected, there is a lot of qualitative similarity in the two curves. From the spectra of the hydrogels it is clear that the band at 1430 cm^{-1} (CH2 symmetric bending) is strongly decreased in intensity, and the band at 1328 cm^{-1} (C-C and C-O cellulose skeletal vibrations) is increased, more strongly in the spectrum of hA. Another important observation made is that the bands at 1162 and 1111 cm^{-1} disappear. Also, by comparing the spectra of the hydrogels it becomes clear that the band at 1630 cm^{-1} (adsorbed water) is more intense in hA than in hC. In addition, clear modification in the region 1500–899 cm^{-1} is seen, which can be attributed to an alteration of cellulose crystalline organization because of the alkali treatment. Also, the decreased intensity of the band at 1430 cm^{-1}, known as the crystallinity band, reflects a decrease of the crystallinity degree of cellulose. It has now been established that the etherification reaction leads to the formation of the local hydrophilic domains for water sorption, and also stops the adjacent cellulose chains from establishing intermolecular hydrogen bonds [21-23].

DISCUSSION AND CONCLUSION

It has been observed that the artificial dielectrics in the form of photonic crystals are very useful for novel applications including the designing and fabrication of fibers, novel lasers with nanostructures, plasmonic photonic crystals, and hydrogel sensors in medicine and biosensors. The versatility of the utility of these materials has been established and well exploited so far, as has been discussed in this paper. The mathematical modeling and synthesis of such devices, and the designing considerations for maximizing their efficiency, as has been discussed very briefly in this paper, in order to give a comprehensive picture about the various aspects of such materials; can be really useful for the researchers to choose the area of their interest in this exciting and rapidly evolving topic. However, more theoretical and experimental investigations are required to be carried out to exploit the utility of these materials. In fact various premier research establishments should combine their efforts, and share the research findings for the rapid growth of this interesting area of research. As they possess unique properties, they are finding applications in various fields including aeronautics and aerospace engineering.

It has now been realized and understood that structural electromagnetic metamaterials can be used for aerospace applications. The aeronautical engineers have already reported the feasibility of fabricating advanced large area tunable structural metamaterials for space applications. The metamaterials are known to offer unique EM possibilities. It has been realized that these may be combined to provide a structural material that is very useful for aerospace applications.

The man-made composites that are scaled smaller than the wavelength, have shown a huge potential for application in acoustics, allowing the production of sub-wavelength acoustic absorbers, acoustic invisibility, perfect acoustic mirrors and acoustic lenses for hyper focusing, and acoustic illusions and enabling new degrees of freedom in the control of the acoustic field. It is important to note that the zero, or even negative, refractive sound index of metamaterials offers possibilities for the control of acoustic patterns and sound at sub-wavelength scales. Inspite of the tremendous growth in research on acoustic metamaterials during the last decade, the potential of metamaterial-based technologies in aeronautics has still not been fully explored, and its utilization is still in its infancy, and hence requires a lot of funding in Research Departments, especially aeronautics. Hence, these principal concepts could very well provide a means to develop devices that allow the mitigation of the impact of civil aviation noise on opportunities are for metamaterials in Aerospace and defense markets. Aerospace and defense market is often considered as the most upcoming sector of the metamaterials market. Hence, this is where much of the R&D funding has gone. However, n-tech's analysis suggests that not a lot of actual commercial revenues have been generated in this part of the metamaterials market. The metamaterials are going to be very useful for designing radars and also in surveillance systems. It has now been realized and understood that structural electromagnetic metamaterials can be used for aerospace applications. The aeronautical engineers have already reported the feasibility of fabricating advanced large area tunable structures for space applications. The metamaterials are known to offer unique EM possibilities. It has been realized that these may be combined to provide a structural material that is very useful for aerospace applications. The man-made composites that are scaled smaller than the wavelength, have shown a huge potential for application in acoustics, allowing the production of sub-wavelength acoustic absorbers, acoustic invisibility, perfect acoustic mirrors and acoustic lenses for hyper focusing, and acoustic illusions and enabling new degrees of freedom in the control of the acoustic field. It is important to note that the zero or even negative, refractive sound index of metamaterials offers possibilities for the control of acoustic patterns and sound at sub-wavelength scales. Inspite of the tremendous growth in research on acoustic metamaterials during the last decade, the potential of metamaterial-based technologies in aeronautics has still not been fully explored, and its utilization is still in its infancy, and hence requires a lot of funding in research departments, especially aeronautics. Hence, these principal concepts could very well provide a means to develop devices that allow the mitigation of the impact of civil aviation noise on the community. There are future opportunities for metamaterials in aerospace and defense markets. Aerospace and defense market is often considered as the most upcoming sector of the metamaterials market. Hence, this is where much of the R&D funding has gone. In view of the discussion of the various topics in this paper, and especially of the serious efforts being made on the utility and applications of metamaterials in aeronautics industry, it can be safely concluded that the metamaterials are going to have many applications in aeronautics industry.

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