Chapter 1

Introduction

1.1 Dissertation organization

In this dissertation, we follow an alternative thesis format, which allows for the inclusion of our published or submitted papers in scholarly journals. Each paper presented as an independent chapter in exactly the same format it was published and it was submitted to the journals. In what follows, we present a brief description of the highlights of each chapter and how it fits in the theme of this work. In addition, a brief abstract of the contents of each chapter is provided at the beginning of this chapter.

In Chapter 1, we present a general introduction to the subject of near field optics and photonic crystals. Our goal is to provide the reader with the basic concept of these fields, and to present a brief explanation of their underlying physics. A rather detailed thorough review of the most relevant theoretical and experimental literature in the areas is provided to get the reader acquainted with the most recent developments in the fields and to set the stage for the discussions provided in the subsequent chapters. The needs as well as the expectations from these theoretical approaches are also highlighted.

In Chapter 2-3 we provide a review of theoretical techniques employed in the current work. While most of these techniques are existing developed methods, the aim here is to provide a comprehensive picture of these methods.

Chapter 3 provides a detailed development of the first of the theoretical methods addressed in the current work. Here, we investigate the so-called plane wave expansion (PWE) method. This method is operated in k-space and is used primarily for mapping the band structure of photonic crystals. Our goal is to provide the reader with the theoretical foundation of this method, and to present a brief explanation of its underlying physics. The highlight of the major strength as well as the limitations and drawbacks of this technique will also be summarized.

Next, our focus in Chapter 4 is on the so-called finite-difference time-domain (FDTD) method. As its name suggests, this method offers a way of probing the temporal as well as the spatial development of wave propagating inside a near field zone and a photonic crystal. The FDTD method has been chosen, among the many available, because of its capability to deal with complicated structures such as those analyzed here. Using different kinds of boundary conditions, the method allows one to deal with many different types of problems: computation of the dispersion diagram, computation of resonant frequency, effective mode volume, Q, and mode pattern in the nanocavity. Indeed, the method proved to be very effective in these calculations because it provides a wealth of data from which it is possible. Again our goal is to provide the reader with the theoretical foundation of this method, and to present a brief explanation of its underlying physics. Finally, a highlight of the major strength as well as the limitations and drawbacks of this technique will also be summarized.

After providing the reader with the previous theoretical foundation, we shift our attention to actual applications of the previous techniques. Chapters 5-8 are a collection of selected papers where the previous methods have been put to use. These chapters comprise the core of the research conducted by the author for fulfillment of the Ph.D. thesis requirements.

Basically, the dissertation can be separated into two parts to be discussed. The first part, we present the analysis and applications of the interaction phenomena between light wave and scatters (e.g. optical fiber, sample and solid immersion lens (SIL) probe system) in the near field zone using 3D finite difference time domain (FDTD) method. In the second part, the high efficiency coupling techniques between silicon waveguide (SWG) and planar photonic crystals (PPCWGs) are proposed using both plane wave expansion (PWE) and FDTD methods.

In the first part, we present the study of some problems in near field shown in Chapter 4 and 5, respectively. Chapter 4 deals with the near field distributions in the subwavelength aperture with sample and optic fiber probe optimization, In this chapter, the use of the FDTD method to get more insight in the near-field distribution of subwavelength aperture with sample and fiber probes are numerically investigated. The treatments of dispersive materials in a time dependent fashion are considered. Several significant factors are also considered successively, e.g., the near-field distribution of subwavelength aperture with sample in an infinite aluminum plane, the characteristics between the near field distribution and the phenomena of depolarization, different kinds of 3D tips (non-coated and metal-coated) used to illuminate the photosensitive sample and the polarizations of the incident electromagnetic field. A comparative study of the near fields generated by non-coated and metal-coated tips is important to determine their relative capability as efficient tools for more insight in the mechanisms responsible for near-field scanning optical microscopy (NSOM) architecture. In the same manner, the role of the tip-sample spacing during the exposure of the sample has also to be assessed to get a better the resulting nanometric dimension field patterns. Besides, the 3D version of FDTD design of field enhancing NSOM probe is illustrated and gives a suggestion for fabricating an optimal probe. This method will yield useful information and guidelines for designing high performance near-field probes.

Having pointed out the way to design the high performance of near field probes, we shift out attention to the application for high density storage. Chapter 5 prevents a solid immersion lens with a conical probe system. A solid immersion lens (SIL) combined with near-field probes which are the conic dielectric probe and the local metallic coating on the SIL probe is designed for optical recording by means of a 3D rather than 2D FDTD method to gain more insight in the near-field distribution. Our computation model is realistic to match the real SIL-probe system. The optical properties of near field distributions between the SIL probe and recording layers are investigated. A promising idea for fabricating a type of the SIL-probe system is proposed. Results of our designation of an optimal SIL-probe system can achieve higher performance (in terms of high throughput and low reflection of the light beam) for optical data storage and microscopy than the conventional metal NSOM probe or SIL used alone.

As regards part 2, we report high efficiency coupling techniques between SWG and PPCWGs using optimal configurations which can remarkably enhance the coupling efficiency at the entrance and exit terminals of PPCWGs. In Chapter 6, we design a mode matching technique for highly efficient coupling between silica waveguides (SWG) and planar photonic crystal (PPC) waveguide. The structure considered here is a 2D square lattice of dielectric rods of Si embedded in a homogenous dielectric medium of SiO_2. The procedures to obtain the optimum defect configuration are discussed in detail. While the transmission efficiency is less than 60% using the conventional PPC taper, the optimized scheme maximizes the power transmission above 90% achieved at a wavelength of 1.55 μm within our investigation when the taper structure and defect parameters are well designed. Besides, one can control the central frequency for optical communications by determining this defect configuration in the optimization procedure.

Now we change the form of lattice structure to a triangular one. In Chapter 7, we report that using a cabin-side-like tapered structures, only containing one pairs of defects, can remarkably enhance the coupling efficiency at the entrance and exit terminals of planar photonic crystal waveguides (PPCWGs).

The PPCWGs are composed of circular dielectric rods setting in 2D triangular lattices. In the simulations, we find that the transmission efficiency reaches up to 90%. Moreover, the suggested structures possess other advantages, such as the shortness of taper, the ease of fabrication and its low cost. It is anticipated that the proposed structures might feasibly apply to the integrated optical circuit compatibility.

A brief comparison between the 2D devise and 3D slab version is given in section 7.4. Besides, we present an efficient mode coupling technique between silica SWGs and a planar photonic crystal heterostructure waveguide (PPCHWG) in Chapter 8.

In Chapter 8, we first present an efficient mode coupling technique between silica waveguides (SWGs) and a planar photonic crystal heterostructure waveguide (PPCHWG) composed of two semi-infinite two-dimensional photonic crystals (PCs) with different filling fractions. By calculating the transmittance at exit of SWG, we found the designed structure to have high coupling efficiency and fabrications tolerance. The maximal transmittance exceeds 90% at wavelength near 1.65 μm. One of the merits of PPCHWGs is high transmission efficiencies acquired without enforcing the introduction of any pair of defects for achieving mode matching. Besides, the width of PPCHWGs can be flexibly controlled by adjusting the lateral separation of two component PCs in PC heterostructures.

We end the work at hand by providing a summary all of our findings in Chapter 9. Recommendations for future work as well as ways of enhancing the current theoretical techniques are also point out.

Chapters 4, 5, and 7 have been accepted and published in scholarly journals. Chapter 4 was deemed acceptable by the Japanese Journal of Applied Physics Part 1, Regular paper, 2004. Chapter 5 was published in the Journal of Applied Physics, Vol. 9., No.7, page 3378-3384, April 1, 2004. Chapter 7 was also accepted by the Japanese Journal of Applied Physics, Part 2, Letter, Vol. 43, No. 8B, 2004. Chapter 6, and 8 have been submitted to Applied Optics and Optic Letter, in peer review, respectively.

1.2 Introduction to near field optics and photonic crystals

Photonics has several advantages over electrons. One of the greatest advantages is that photons can travel in a dielectric material at a much greater speed than electrons in a metallic wire. Another advantage is that the bandwidth of the dielectric materials is larger than that of a metal. For example, conventional fiber-optic communications systems such as those in telecommunications industry have bandwidths of only a few hundred kilohertz. In addition, photons are not as strongly interacting as electrons, thus substantially reduce the energy losses in practical system [1].

1.2.1. What is near field optics?

Near-field optics studies the behavior of light fields in the vicinity of matter, where light is structured in propagating and evanescent fields. Near-field optical microscopy is the straightforward application of near-field optics.

Near-field optics, or NFO, very roughly speaking describes optics in dimensions of 100 nm or less. The microscope based on this principle, the Scanning Near-field Optical Microscope (SNOM, or NSOM for others), allows to perform optical microscopy with a spatial resolution better than 200 nm, i.e. beyond the diffraction limit. Optical microscopy, with its variety of contrast mechanisms (and thus accessible sample properties) and with a spatial resolution superior to what can be achieved by conventional microscopes today, is a very useful tool.

Optical microscopy has come a long way from Zacharias Jansen's first microscope at the end of the 16th century to today's highly developed microscopes. A number of different contrast mechanisms allow broad applicability as a routine tool in biology, medicine, materials research, and many more. It is hard to think of any other tool for routine and exploratory tasks that is as widespread as optical microscopy.

The impossibility of getting a subwavelength resolution in optics has been known for a long time (in the late 19th century). It was expressed in terms of diffraction theory more than one century ago by Ernst Abbe, a German physicist who predicted the existence of a resolution limit. Later it was reformulated by the Englishman Lord Rayleigh in the following very concise form:

$$r \geq \frac{1.22\lambda}{2n\sin(\theta)} \tag{1.1}$$

It stipulates that two point objects will be seen separately only and only if the distance r between the two points is greater than a quantity connected to the wavelength λ of the light beam, to the index n of the medium and to θ, the semi-angle of aperture of the objective used for collecting and focusing the light beam onto the detector. This relation is known as the Rayleigh criterion. This fundamental law states that with light, as with any other wave phenomenon used for microscopy, it is not possible to spatially resolve details that are located closer together than approximately half the probing wavelength. For optical microscopy, typically operating at a wavelength of 500 nm (the visible spectrum ranges from 400 nm to 700 nm), the lateral resolution is thus limited to about 250 nm.

Recently, two different approaches have been demonstrated to break the diffraction limit of resolution. Both approaches differ from conventional optical microscopy in that they don't form images of the object by means of lenses, but rather collect the optical response of the sample point by point.

In Laser Scanning Confocal Microscopy, both the sample illumination and the light collection is focused onto the same spot on the surface of the sample (or even inside the sample). The sample is scanned and at every location the light intensity is recorded by a computer. The increase of resolution is achieved by the overlap of two Gaussian focal profiles, effectively narrowing the profile width and thus improving the resolution.

The second approach, named Near-Field Scanning Optical Microscopy (NSOM) [2-11], brings a small optical probe very close to the sample surface, in the region called "near-field". Here, at distances smaller than the wavelength away from the surface, also those waves can be probed that do not propagate, but rather decay exponentially perpendicular to the surface. It can be shown fairly easily that it in this evanescent field the k-vectors parallel to the surface can be fairly large, corresponding to small lateral (spatial) dimensions. As opposed to conventional as well as to laser scanning microscopy which are far-field microscopies, NSOM requires the close proximity between probe and sample.

This concept of near-field microscopy had been proposed already in 1928 by Edward Hutchinson Synge; however, the technical difficulties could not be overcome. It is amazing to see how closely the proposed device resembles today's instruments! A number of further proposals followed, probably without knowing of the earlier publications. Finally, after the demonstration of the Scanning Tunneling Microscope (STM), the principle was experimentally demonstrated in 1984. It´s fair to say that SNOM is a rather young technique, and by far not yet established in the way conventional optical microscopy is.

With NSOM we have tool in hand that combines the advantages of optical microscopy (a whole variety of different contrast mechanisms, the possibility of spectroscopy for chemical identification, the fact that we are used to see (probe optically) the world around us everyday), with the high resolution capability of scanned probe microscopies such as Scanning Tunneling Microsocopy (STM) and Scanning Force Microscopy (SFM). Today NSOM has a proven spatial resolving power of around 50 nm. That is definitely less than what STM and SFM are capable to, but comes along with valuable information only accessible with optical contrast. One should look at it as a complementary tool with some room for improvement.

The strength of near-field optical microscopy over other scanning probe techniques is that it allows to observe a whole variety of (optical) sample properties. If you are just interested in sample topography, force or tunneling microscopy will do a better job. With SNOM however you have the choice of additional, often complimentary, contrast mechanisms: (1) monitoring the light intensity allows to image changes in transmittivity or reflectivity, or in index of refraction. (2) Polarization contrast shows sample birefringence and many aspects of orientation on surfaces. (3)Wavelength contrast (or "fluorescence microscopy") lets one observe luminescence (photo- as well as electro-excited) and (molecular) fluorescence phenomena, as well as to perform spectroscopy for chemical identification.

Many objects that to the unaided eye appear optically isotropic show various kinds of contrast when viewed through optical polarizers, illuminated by polarized light. This polarization contrast is induced by dichroism (the material shows selective absorption of one of two orthogonal polarization directions) or birefringence (the material shows different index of refraction for the two orthogonal polarization directions). Well-known examples are dichoric polarizers or the birefringent crystal calcite which forms double images of objects viewed through it.

Polarization contrast NSOM is not only interesting since its resolution is potentially better than that of conventional optical microscopy. The combination of optical and topographic information obtained by shear-force imaging is equally attractive. To experimental schemes of polarization NSOM can be distinguished, depending on whether the direction of input polarization is kept fixed, or whether it is being modulated. Working with one fixed input polarization direction is easier to achieve for technical reasons. Usually, fiber probes show asymmetries in taper shape and aperture, which leads to a partial depolarization of the injected light. Often, one direction of polarization can be found where the fiber depolarization is small, allowing to perform polarization contrast imaging with reasonably small instrumental signal background.

In theoretic approaches on NSOM, it has to be kept in mind, that tip and sample are a system. They belong together and influence each other. This results in a complicated distribution of the electric field between tip and sample that can hardly be treated analytically and has to be studied numerically. Our research in this dissertation with SNOM is directed towards the following interests: (1) better understanding of near-field optics (2) interaction of sample features with the near-field (3) optimal near field probe design (4) optimal design of solid immersion lens with conical probe system for high performance of optical data storage.

1.2.2. What is a photonic crystal?

Semiconductor materials have played a huge role in virtually all aspects of everyday life since their discovery over many years ago. The drive towards miniaturization and high-speed performance of highly-integrated circuits has stimulated tremendous research efforts in both academia and industry. However, some of the unfortunate consequences of electric circuit miniaturization and increased resistance and increased power dissipation. Furthermore, higher circuit speeds lead to increased sensitivity to signal synchronization, Research is therefore beginning to turn towards the use of photons instead of electrons as the primary information carrier [1].

Photonic crystals are dielectric materials that contain a periodicity in dielectric constant. The periodic constant in static dielectric constant can create a range of forbidden frequencies called a photonic band gap. Electromagnetic modes with energies lying within a band gap cannot propagate through the photonic crystal and are therefore forbidden. The underlying physical principle of operation of such crystals is rather simple: an electromagnetic wave passing through an array of periodic scatters will undergo destructive interference for certain combinations of wave vectors at certain frequencies, thus forbidding their propagation.

In recent years[1,12], there has been a great interest in determining the photonic band structures, also know as dispersion curves, for electromagnetic waves propagating in various 2-D and 3-D photonic crystals. The goal of these investigations has been to determine whether the photonic band structures formed by the branches of these dispersion curves are separated by any photonic band gaps. To be useful, the photonic band gap must exist for all wave vector values in the Brillouin zone for the photonic crystal under study.

Periodic dielectric structures have for years played an important role in many branches of physics. For example, interference coatings have become indispensable in the field of wave optics. The interference coatings are actually layered dielectric structures that have a quarter wavelength periodicity in their index of refraction. This dielectric periodicity creates a photonic band gap in electromagnetic dispersion curves for those electromagnetic waves that propagate perpendicular to the layers. This 1-D photonic band gap makes 1-D periodic dielectric structures valuable as highly ideal reflective mirrors. An example of a popular device that takes advantage of this 1-D photonic band gap is the Fabry-Perot resonator. The prospect of similarly useful device application has provided tremendous motivation to create both 2-D and 3-D photonic crystals in which there exists a photonic band gap. Photonic crystals therefore offer the possibility of allowing for unprecedented control and manipulation of light. The exciting potential of photonic crystals is the ability to have unprecedented control over the properties of light within the photonic crystal. Yablonovitch[13] and John [14] were the first to suggest the idea of designing materials that might affect the properties of photos analogous to the way that ordinary semiconductor crystals affect the properties of electrons. It was suggested that structures that were periodic in dielectric constant could dictate which electromagnetic modes might exist.

There is a strong analogy between photonic crystals and semiconductor crystals. An electron propagating through a semiconductor crystal sees a periodic potential created by the atomic lattice. Because of Bragg-like diffraction from the atoms in the semiconductor crystal lattice, a gap in allowed electron energies opens up. Electrons with energies in the forbidden range cannot propagate in the semiconductor crystal in any direction. In a photonic crystal the analogous periodic potential, (the mechanism causing the Bragg-like diffraction), is due to a lattice of periodic dielectric contrast. An example is a periodic arrangement of dielectric columns in two dimensions or of dielectric spheres in three dimensions. If the dielectric constants of the columns or spheres are different enough from the dielectric constant of the background crystal then Bragg-like scattering of the dielectric interfaces can produce many of the same phenomena for photons as the atomic potential of a semiconductor crystal creates for electrons. Therefore, a photonic band gap in a photonic crystal may be viewed as the optical analogue of the electronic band gap in a semiconductor.

However, in a photonic potential, thereby allows the gap to be controlled. On the other hand, in an electronic crystal the potential is strong enough to result in a gap for many types of crystal lattices, whereas in photonic crystals the existence of a photonic band gap is highly dependent on the lattice geometry and dielectric contrast. As a result, there are fewer examples of 3-D photonic crystals which possess photonic band gaps.

A photonic crystal might therefore be engineered to possess a photonic band gap for a specific range of frequencies for which electromagnetic waves are forbidden to exist within the crystal. The electromagnetic modes would be forbidden in a perfectly periodic photonic crystal. However, if there is a defect in the otherwise perfectly periodic crystal, localized photonic states could exist within the photonic band gap. A point defect within an otherwise perfectly periodic photonic crystal might act like a microcavity, a line defect might act like a waveguide, and a planar defect might act like a perfect mirror [1].

1.2.3 Two-Dimensional photonic crystals

There have been several previous studies [12,15], of the photonic band structures of both 2-D and 3-D photonic crystals. A 2-D photonic crystal is periodic along two of its axes and homogeneous along the third. In this dissertation, two classes of 2-D photonic crystalare considered. The first one is a photonic crystal formed by a square lattice of dielectric columns with dielectric constant ε_a in a dielectric background of dielectric constant ε_b. The second one is a photonic crystal made by arranging the dielectric columns in a triangular lattice.

1.2.3.1 Square Lattice Photonic Crystals

Figure 1.1 illustrates the first class of two-dimensional photonic crystals to be studied, namely, the square lattice of columns of high dielectric constant ε_a in a background of low dielectric constant ε_b.

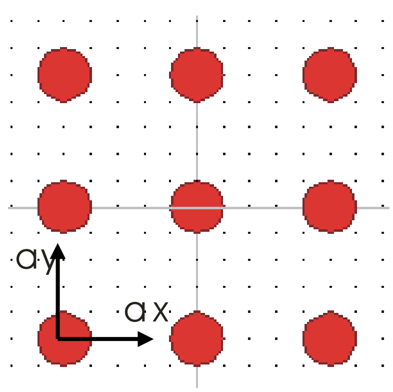

Fig. 1.1 The two dimensional square lattice of columns of high dielectric ε_a in a background of low dielectric constant ε_b.

The square lattice structure consists of a periodic array of parallel dielectric columns of circular cross section and dielectric constant ε_a whose intersections with a perpendicular plane from a square lattice. The dielectric columns are embedded in a dielectric material whose dielectric constant is ε_b .

1..2.3.2 Triangular Lattice photonic crystals

The second class of 2-D photonic crystals to be consider is illustrated in Figure 1.2 shows a 2-D photonic crystal that is comprised of a triangular lattice of columns of high dielectric constant ε_a in a background of low dielectric constant ε_b .

The triangular lattice structure consists of a periodic array of parallel dielectric columns of circular cross section and dielectric constant ε_a whose intersections with a perpendicular plane from a triangular lattice. The dielectric columns are embedded in a dielectric material whose dielectric constant is ε_b .

The square lattice and triangular lattice photonic crystals are of interest because dielectric structures with these symmetries are now being fabricated for experimental studies of photonic band structures [15].

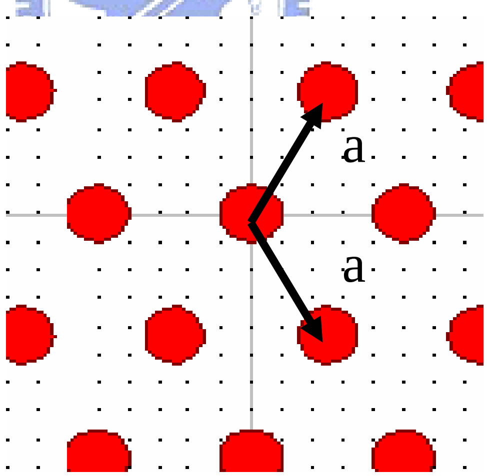

Fig. 1.2 The 2-D triangular lattice of columns of high dielectric constant ε_a in a background of low dielectric constant ε_b .

1.2.4. Photonic band structure

The analogy between photonic crystals and semiconductor crystals is more easily seen when are considered the so-called master equation for photonic crystals. In the absence of external currents and sources, Maxwell's equations can be re-written, in the following form that is very similar in appearance to the Schrodinger equation. The equation for photonic is given as

$$\nabla \times \frac{1}{\varepsilon(r)} \nabla \times H(r) = (\frac{\omega}{c})^2 H(r) \qquad (1.2)$$

Where H (r) is the magnetic field of the photon, ω is its frequency, c is the speed of light and $\varepsilon(r)$ is the macroscopic dielectric function describing the photonic crystal. Equation 1.2 represents a linear Hermitian eigenvalue problem. The eigenvalues, or eigenfrequencies, and determined entirely by the microscopic dielectric function ε (r). If $\varepsilon(r)$ is perfectly periodic, as in a perfect photonic crystal, the solutions are characterized by a wave vector k and a band index n. The collection of eigenfrequency dispersion curves as a function of the wave vector, usually taken in the first Brillouin zone, is referred to as the photonic band structure.

The photonic band structure depends on the lattice constant, a, the radius of the dielectric column in two dimensions, or sphere in three dimensions, and the dielectric contrast between the cylinder or sphere relative to the material making up the background of the photonic crystal. One of the key difference between the study of the photonic band structure and electronic band structure is that in the study of photonic crystals, (through Maxwell's equations), there is no fundamental length scale [1]. In the study of semiconductor crystals, (using Schrodinger equation), the potentials have a fundamental length scale on the order of the Bohr radius. Therefore crystals that differ only in their absolute scale will have very different electronic band structures. The situation is quite different with photonic crystals, where solutions at different length scales differ by a simple scale factor. Therefore, the solution for the photonic band structure at one length scale determines the photonic band structure at all other length scales.

Photonic band gap may exist for a variety of photonic crystals. The gap is a region of frequencies for which no electromagnetic modes may exist within the photonic crystal for any value of the wave vector k within the Brillouin zone. The band above a photonic band gap is commonly referred to as the dielectric band. These photonic band structure terms are analogous with the use of the terms condition band and valence band for the electronic band structure of semiconductor crystals.

Since electromagnetic modes with frequencies that are within the photonic band gap are forbidden, spontaneous emission will be forbidden in case in which the photonic band gap overlaps the electronic band edge. This suppression of spontaneous emission can dramatically improve the performance of many optical and electronic devices [15]. It is therefore desirable to obtain a photonic band structure with a photonic band gap, within which the propagation of the electromagnetic waves is forbidden for all wave vectors k within the Brillouin zone.

Early theoretical studies of the propagation of electromagnetic waves in photonic crystals were based upon the scalar-wave approximation [6] in which the vector nature of the electromagnetic field is ignored. These calculations did not give correct results for the band structure [12]. Recent theoretic studies of photonic crystals [1,12,17], therefore rely on the fully vectorized electromagnetic field.

The translational symmetry of a photonic crystal is broken by addition of a dielectric defect. This is essentially of a change in the dielectric constant of a specific region within the otherwise perfectly periodic photonic crystal. These electric defects may result in defect states within the crystal. Dielectric defects result in defect states within the photonic band gap just below the air band, while air defects result in defect states just above the dielectric band of the photonic band structure [1,18]. These are similar to the impurity levels in semicinductors.

References

[1]J. D. Joannopoulous, P.R. Villeneuve, and S. Fan, Nature 368, (1997) 143

[2] Heinzelmann et al., "Forbidden light scanning near-field optical microscopy", J. Micr. 177, 115(1994)

[3]Novotny et al., "Light Propagation through Nanometer-Sized Structures: The Two-Dimensional-Aperture Scanning Near-Field Optical Microscope", J. Opt. Soc. Am. A 11, 1768(1994)

[4] Hecht et al., "Combined aperture SNOM/PSTM: best of both worlds?", Ultramicr. 57,

228(1995)

[5] Hecht et al, "Tunnel" near-field optical microscopy: TNOM-2", in "Photons and Local Probes", NATO ASI Series E: Applied Sciences, Vol. 300 eds. O. Marti and R. Moeller, Kluwer, 93(1995)

[6] Novotny et al., "Light Propagation in Scanning Near-Field Optical Microscopy", in "Photons and Local Probes", NATO ASI Series E: Applied Sciences, Vol. 300 eds. O. Marti and R. Moeller, Kluwer, 21(1995)

[7] Hecht et al., "'Tunnel' Near-Field Optical Microscopy: TNOM-2", Ultramicr. 61, 99 (1995)

[8] Novotny et al., "Near-field, far-field and imaging properties of the 2-d aperture SNOM", Ultramicr. 57, (180)1995

[9] Van Labeke et al., "A theoretical model for the Inverse Scanning Tunneling Optical Microscope (ISTOM)", Opt. Comm. 114, 470(1995)

[10] Barchiesi et al., " The inverse scanning tunneling near-field microscope (ISTOM) or tunneling scanning near-field optical microscope (TSNOM) 3D simulations and applications to nano-sources", Ultramicr. 61, 17(1995)

[11] Hecht et al., "Facts and Artifacts in Near-Field Optical Microscopy", J. Appl. Phys. 81, 2492(1997)

[12] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, “Photonic crystals: molding the flow of light”, (New York: Princeton University Press, 1995)

[13] E. Yablonovitch, Phys. Rev. Lett. 58, 2095 (1987)

[14] S. John, Phys. Rev. Lett. 58, 2486 (1987)

[15] M. Plihal, and A. A. Maradudin, Phys. Rev. B 44, 8565 (1991).

[16] K. M. Ho, C. T. Chan, and C. M. Soukoulis. Phys. Rev. Lett. 65, 3152 (1990)

[17]R. D. Meade, A. M. Rappe, K. D. Brommer, J. D. Joannopoulos, and O. L. Alerhand, Phys. Rev. Lett. 67, 3380 (1991)

[18]E. Yablonovitch, T. J. Gmitter, R. D. Meade, A. M. Rappe, K. D. Brommer, and J. D. Joannopoulous, Phys. Rev. Lett. 67, 3380 (1991).