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Plasma Photonic Crystal

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1. Introduction

Recently, there has been a rapid growth in the use of plasma for industrial applications where the use of plasma-based technologies offer distinct advantage over the conventional technologies (Kumar, 2011c). A number of spin-off plasma based technologies have spawned in the area of plasma-microwave interactions and plasma stealth technology. Plasma is the fourth state of matter and its material properties (electric permittivity and magnetic permeability) can be tuned by changing plasma parameters for electromagnetic radiations. As it is well known that electric permittivity (ε) and a magnetic permeability (μ) are the fundamental characteristics which determine the propagation of electromagnetic waves in matter. Here, it may be quite interesting to study the electromagnetic wave propagation in the plasma. Plasma can be used as metamaterials for negative refrction of electromagnetic waves (Kumar, 2010a; Kumar 2011d).

2. Photonic crystals (PCs) for negative refraction

Photonic crystals (PCs) are structures with periodic arrangement of dielectrics or metals, which provide the ability to manipulate the propagation of electromagnetic waves. In fact the lattice constant of common materials is 0.2-1 nm, i.e., much shorter than the wavelength of visible light (a few 100 nm). This is the reason why the response of such materials on the electrical and magnetic fields of light wave can be described by macroscopic parameters ε and μ. In 1987, anomalous refraction properties of PCs were reported based on a numerical analysis with transfer matrix method (Yablonovich, 1987). The light propagation in the PCs can not be considered as an average effect of atoms as in common crystals. In contrary, light propagation in PCs is the result of Bragg diffraction for each atom. Hence the periodic structure of the PCs is very important. The macroscopic constant ε and μ can not describe the light propagation in PC and the light refraction at the PC boundary. More precisely, light waves in PCs should be considered as the Bloch waves but in the so-called envelope function approximation they may be considered as plane waves.

An effective index of refraction for the crystal is used to describe the overall reflectivity form the photonic crystal:

$$\eta = c\frac{d\omega}{dk} \tag{1}$$

Thus, calculating band structure of a PC numerically leads to calculation of η. From the experimental point of view η can be calculated by Snell's law. Hence, the negative refraction can be realized also with PCs that is in contrast to the composite metamaterials pave inhomogeneous media with a lattice constant comparable to the wavelength. Although both ε and μ are positive in dielectric PCs and metallic photonic crystals (MPCs), phenomenon of negative refraction and super resolution can be expected from peculiarities of the dispersion characteristics of certain PCs. The main advantage of PCs over composite metamaterials (CMMs) currently is that they can be more easily scaled to 3D and adapted to visible frequencies (Parimi et al, 2004). Negative refraction at microwave frequencies was observed in both dielectric and metallic PCs, for example, using a square array of alumina rods in air (Cubukcu et al, 2003). 2D and 3D PCs consisting of alumina rods were used for the demonstration of negative refraction in the microwave and millimeter wave range. Two techniques namely, manual assembly of alumina rods and rapid phototyping were used in this study for fabricating low-loss PCs (investigated in the wave range form 26 GHz to 60 GHz). The negative refraction in a metallic PC with hexagonal lattice acting as a flat lens with out optical axis at microwave frequencies was reported at 10.4 GHz for TM mode (Parimi et. al, 2004). Such PC contains cylindrical copper rods, are in triangular lattice, in which negative refraction was found for both TM and TE mode propagation between 8.6 and 11 GHz (TM mode) and between 6.4 and 9.8 GHz (TE mode). Hence, extensive experimental and simulation results were achieved, which pave the way to a variety of well tailored PCs structures. However, the advantages of metallic PC were reported to be highest dielectric constant, low attenuation, and the possibility of focusing. Most of efforts have been dedicated to the engineering and extension of the functionalities of metamaterials or PCs at terahertz (Yen et al, 2004 ; Padilla et al, 2006, Chen et al, 2006) and optical frequencies (Linden et al, 2004; Soukoulis et al, 2007). Negative refraction of surface plasmons was also demonstrated but was confined to a two-dimensional waveguide (Lezec et al, 2007). Three dimensional optical metamaterials have come into focus recently, including the realization of negative refraction in semiconductor metamatetrials and a 3D magnetic metamaterial in the infra red frequencies. However neither of these had a negative index of refraction (Liu et al, 2008 ; Hoffman et al, 2007). Three dimensional optical metamaterial with a negative refractive index has been also demonstrated recently (Valentine et al, 2008). Negative and positive refaction tubability of x-band microwve in MPC have been achieved recently by making defults or holes (Kumar, 2011a).

3. Plasma photonic crystal (PPC)

In previous section, we have seen that negative refraction of electromagentic wave is possible by photonic crystal. We now interested to study the plasma photonic crystal due to its applications over the convetional PCs. The plasma photonic crystals (PPCs) are artificially periodic array composed of alternating thin unmagnetised or magnetized plasmas and dielectric materials or vacuum (Hojo and Mase, 2004). It is well known that nonmagnetised plasma can be characterized by a complex frequency-dependent permittivity medium. On the other hand, the unmagnetised plasma is frequency dispersive medium. The refractive index of collisionless unmagnetised plasma that is determined by electromagnetic wave frequency and plasma frequency is less than one. Dispersion relation of propagating electromagnetic waves in nonmagnetised plasma can be modified if bulk plasma is replaced by a microplasma array (Park et al, 2002), which is analogically understood from the extensive studies of photonic crystal. Hence in plasma photonic crystal, array of periodic micro plasmas are used at the place of array of dielectrics or metals in the conventional photonic crystals. One or two dimensional layers of array of micro plasmas make forbidden bands for wave propagation are formed beyond the bulk cut of frequency (electron plasma frequency) due to periodicity, where one can refer to such a functional structures as plasma photonic crystal. A photo of plasma photonic crystal is given below in Fig.1.

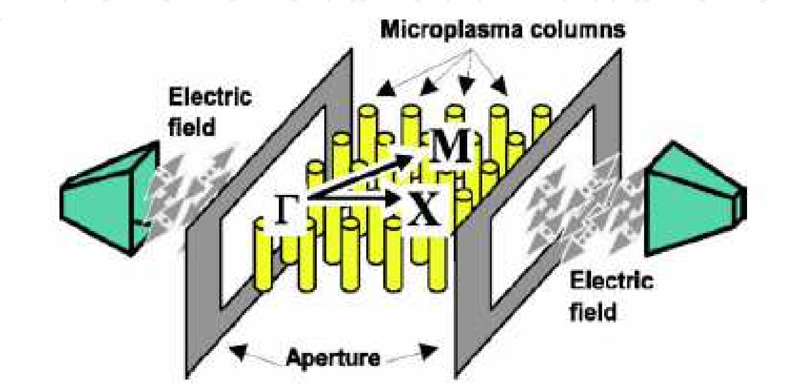

Fig. 1. Plasma photonic crystal

We know that plane-wave-expansion method has been widely used to analytically derive photonic band diagram of two-and three-dimensional dielectric periodic structures (Ho et al, 1990; Phihal et al, 1991). Dielectric constant of plasma can be obtained considering the field components in electromagnetic waves proportional to $\exp.[j(\omega t - k.x)]$, where k and x are the complex wave number and spatial position vector, respectively. The dielectric constant as a function of frequency $\varepsilon_p(\omega)$ inside a cold plasma column with electron plasma frequency (ω_{pe}) is written as

$$\varepsilon_p = 1 - \left(\frac{\omega_{pe}}{\omega}\right)^2 \frac{1}{1 - j(\upsilon_m / \omega)} \tag{2}$$

where υ_m is the electron elastic collision frequency determined by neutral gas pressure and elastic collision cross section. In metal cases, a similar value (γ) to υ_m was used as an inverse of electron relaxation time, and γ was much smaller than ω and ω_{pe} (Kuzmiak and 1997) it is also possible that υ_m is comparable to ω and ω_{pe} where electron density is around 10^{13} cm^{-3} at a gas pressure around atmospheric pressure. Therefore plane-wave expansion method with Drude model in collision plasma has been studied (Sakai et al, 2007) for plasma photonic crystals. Experimental demonstrations have also been performed (Sakai et al, 2005 ; Sakaguchi et al, 2007) those typical parameters are summarized below,

- One and two dimensional periodic structures have been studied.
- In 2 D structures, a mesh type DBD (Dielectric Barrier Discharge) electrode assembly, mounted at 6 mm separation from third electrode (Micro-hollow-cathode-discharge MHCD like configuration).
- Array forms a 4.4 x 4.4 cm^2 squire lattice of plasma columns.
- Array size 33 x 33 lattices, where 33 rows of a micro plasma column with diameter of 0.6 mm.

- Lattice constant = 2.1 mm to 2.5 mm.
- Squire hole with opening 1.4 mm x 1.4 mm.
- He, N_2, and Ne gas is used.
- For generation of microwaves, signal generator of 33-50 GHz and 50 – 75 GHz are used.
- Pyramidal horn antennas are used for transmitting and receiving microwaves.

Several experimental studied have been conducted with the help of given experimental set-up and parameters. Important results which emerged from the studied are listed below,

- Lattice structure of micro-plasma arrays behaves as a photonic crystal similar to solid dielectrics.
- A millimeter wave at 33-110 GHz was injected into two-dimensional plasma column array, and the transmitting signal through such array attenuated less than 20%.
- Band gap forms by periodic dielectric constant above the electron plasma frequency $\left(\omega > \omega_{pe}\right)$ and propagation of flat bands below the plasma frequency $\omega < \omega_{pe}$. Hence structure of photonic crystal play role rather then cut-off conditions.
- Band gap frequency could be varied by changing the lattice constant, leading to a function of dynamic and time-controllable band-stop filter in millimeter and sub terahertz regions.
- 30 rows of plasma columns are similar in the case of 17 rows of metal due to a lower ratio of dielectric constant between plasma and vacuum region, plasma photonic crystals require more rows than case of an ordinary photonic crystal.

4. Plasma crystal as photonic crystal

So far we have studied about PCs and plasma photonic crysals. It is quite interesting to describe the plasma crystal as photonic crystal due to its applications over the PCs and PPCs. Infact coulomb lattices of charged dust grains are called plasma crystals, which can be generated in laboratory in dusty plasma experiments (Morfill et al, 1997). Plasma crystals are composed dust grains that become electrically charged to very high charge states while thermal kinetic energy of the grains remains low. In plasma crystal composed of negatively charged dust grains, the dust grain radius is typically in the order of a few micrometers, while the average intergrain distance is on the order of a few hundreds micrometers, with variations in different experiments (Morfill et al, 2002). Therefore plasma crystals generated in the laboratory generally have only a few layers in the vertical dimension owing to gravitational compression, although recently a three-dimensional structure has been demonstrated (Zuzic et al, 2000). However, plasma crystal has some similarities to colloidal crystal, which are colloidal suspensions of ordered charged particles in solvents. Due to Bragg scattering properties, colloidal crystals have applications as narrow band rejection filters in optics. Tunable colloidal crystal in the optical, ultraviolet and infrared have also been demonstrated in which the particle size or spacing charge with temperature to tune the diffraction (Weissman et al, 1996). Recently, a magnetically tunable optical filter comprising a ferro-fluid based emulsion cell has been discussed (Philips et al, 2003). Viewing above it can be noticed that if dust plasma crystal can be generated in sufficient large multilayer closer-packed configuration, they may have similar use as filters in the longer wavelength terahertz (THz) regime. A possible experimental prototype of magnetically controlled and tuned plasma crystal in dusty plasma is shown in Fig. 2. With the help of above study, THz refraction or scattering can be studied.

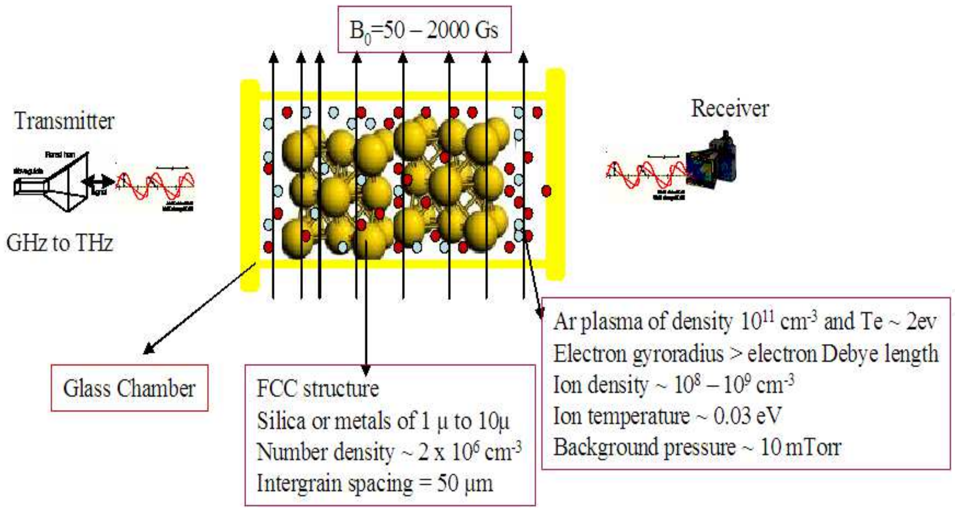

Fig. 2. A prototype to present EM wave transition from plasma crystal

5. Plasma in photonic crystal

In this section experimental study on plasma added photonic crystal (hybrid plasm photonic crystal) is presented. We have seen that negative refraction at microwave frequencies was also observed in both dielectric and metallic PCs. Although, research indicates that the MPC is suitable for negative refraction (Kumar 2011a), however, to date tunability in the fabricated MPC to control the wave propagation has not been achieved. From this aspect, plasma can be a good candidate to replace metal or dielectrics from PCs because plasma is a frequency dependent dispersive medium and its refractive index can be determined by electromagnetic wave frequency and plasma frequency (Ginzberg, 1970; Hojo et.al 2003; Hojo and Mase, 2004) has proposed that plasma photonic crystals (PPCs) are artificially made periodic arrays composed of alternating discharge plasma and other dielectric materials (including vacuum). On the bases of different approaches, two types of PPC are being studied. In the first type of PPC, cylindrical glass rods or dielectrics forming a crystal lattice are immersed in discharge background plasma (Laxmi and Parmanand, 2005; Liu, et al, 2006; Hojo et al, 2006; LIU et al, 2009) while the second type consists of cylindrical rods of discharge plasma that constitutes a crystal lattice in vacuum or air (Sakai, et al, 2005; Sakai et al, 2005; Sakai and Tachibana, 2007). It can also be composed of plasma with spatially periodic density variation, which can be induced naturally in plasmas i.e in the presence of laser pulses in underdense plasmas (Botton and Ron, 1991 ; Zhang et al, 2003; Wu et al, 2005 ; Yin et al, 2009), dust plasma crystals (Rosenberg et al, 2006), self-organised small plasma blobs or patterns (Fan et al, 2009 ; Kumar and Bora, 2010a ; Kumar, 2011c), etc. However theoretical and experimental studies have been going on since last few years to find out the possible applications of PPC over the conventional PCs, although there is no strong evidence of negative refractive index or metamaterial properties of PPC. Meanwhile, difficulties in the construction of PPC have been experienced during experimental realizations. Even after a long research history of MPC and PCC, a number of problems related to controllability and fabrications in both PCs are still unresolved. There is, however, plenty of scope to work on a hybrid PCs (Kumar , 2009a; 2009b, 2011b, 2011d) of MPC and PPC in such a manner so that properties of both PCs can be utilized. Hence, the motivation of this study is to investigate the effect of a plasma column to control the microwave propagation through MPC as presented in Fig 3.

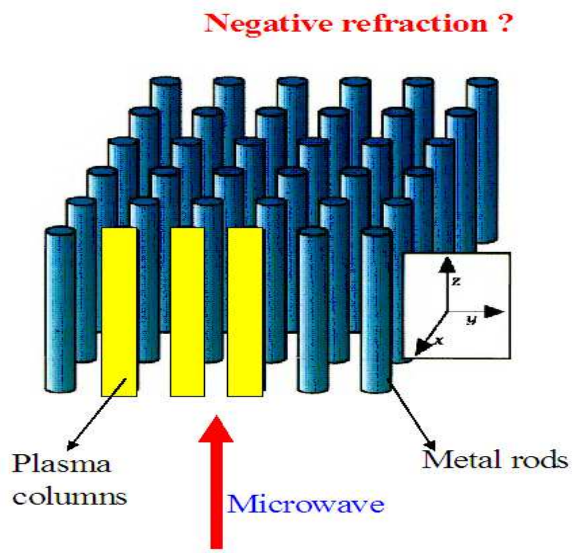

Fig. 3. Hybrid plasma photonic crystal

5.1 Selection of plasma parameters

Our motivation for the study to use plasma column in place of copper rods lies in the fact that by switching OFF and ON plasma, which can be formed and destroyed rapidly, and microwave refraction can be controlled. Hence, to accomplish such purpose it is required to study the characteristics of plasma at X-band frequency microwave (18 GHz) to obtain its behavior close to the metallic copper rods. Hence phase difference in 18 GHz microwave is calculated using reflection coefficient of copper and plasma with the help of relative reflective index ($\varepsilon_r = -0.40 - 1.26i$) and conductivity ($\sigma = 1.24 - 1.4i$). Reflection behavior of microwave from metal and plasma is shown in Fig. 4. The phase difference and path difference are achieved as 2.5 radian and 6 mm respectively.

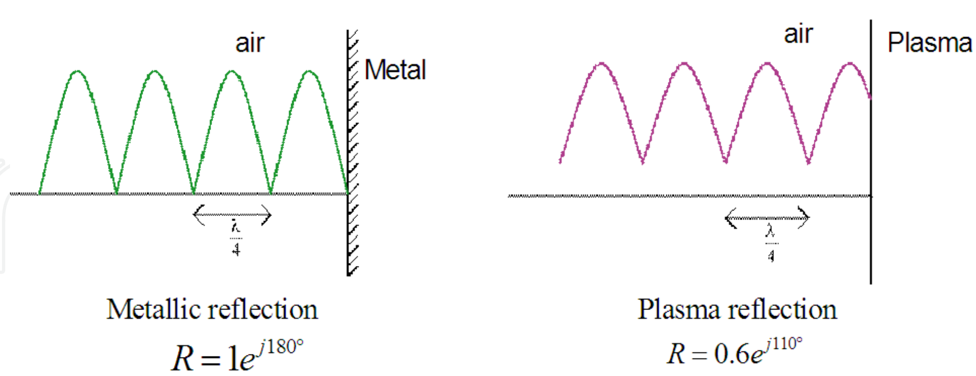

Fig. 4. Reflection of 18 GHz microwave from metal and plasma medium

The plasma is considered as a homogeneous cylindrical channel with complex relative electric permittivity given as

$$\varepsilon(r) = 1 - \left(\frac{\omega_{pe}}{\omega}\right)^2 \left(1 - i\frac{\upsilon_m}{\omega}\right)^{-1} \tag{3}$$

where ω_{pe} is the electron plasma angular frequency, ω is the angular frequency of the incident wave and υ_m is the electron-neutral collision frequency. We see that in order to obtain a significant effect of the plasma for reasonable values of the plasma channel diameter, the plasma density should be in the range of 5 x 10^{12} cm^{-3}. Plasma parameters are precisely chosen to full fill the conditions. Possible precautions for cut-off criteria, collisionality and skin depth effect have been considered. The calculated values of these are given below in Fig. 5.

5.2 Experimental set-up

To accomplish the motivation of this study an experimental set-up is made (This experiemnt was performed in GREPHE, LAPALCE, Toulouse, France). A schematic of experimental set-up for measuring the microwave transmission through metallic photonic crystal (MPCs) with and without plasma column is shown in Fig.6, where a MPC, glass chamber, horn antennas, etc. are presented. A triangular MPC is made by 33 copper rods of diameter 2 mm and length of 100 mm, which are fixed with lattice constant of 10mm in two flanges or discs made by dielectrics in such a way so that different structures of MPC can be configured. Metallic photonic crystal is placed in a glass chamber to carry out experiments with and without plasma column. MPC is kept at the centre of the glass chamber in such a manner that transmitter and receivers can be aliened with the MPC and plasma columns. Two suitable canonical horn antennas are used as transmitter and receiver for X-band microwave. Transmitting horn antenna is fixed and receiving horn antenna can be moved around the MPC form 0^0 to 360^0. Both antennas are used in far-field region form the MPC. The heights of both the antennas are same from the ground. A microwave generator is used to generate X-band microwave (2 GHz-28GHz). A vector network analyzer (VNA) is attached with both the antennas to measure the transmission coefficient. An angle chart is made on the ground level to measure the angle of the position of the receiver from the origin of the MPC. A microwave absorber is used to absorb the microwave so that reflected microwave cannot affect the measurements. In order to investigate the application of plasmas in MPC experiments are conducted with and without plasma column at different places; thus, experimental set-up is modified as follows. In the first set of experiments in which plasma column is formed at the place of central rod of the front row in MPC and in the second set of experiments plasma column is formed between MPC and position of transmitter.

Same discharge mechanism can be used to form the plasma column in all the experiments, so the details of discharge mechanism and formation of plasma columns are common. It is well known that micro-discharge can be used to produce large volume plasma columns up to atmospheric pressure (Kunhard, 2000 ; Park et al, 2003; JING and WANG, 2006). Therefore, micro-discharge is also used to form plasma column in and out of MPC (Kumar, 2009b). For this purpose, three electrodes are made of molybdenum foil and alumina is used as a dielectric to make sandwich of electrodes with the hole diameter of 0.5 mm to 1 mm. High temperature glue is used to pack the electrodes and alumina. Two DC power supplies are used to produce voltage differences between electrodes. Length of the plasma column is equal to the separation between electrodes and, of course, length of plasma column can be varied by changing the separation of electrodes. Typical cathode voltage is 800 V and anode voltage varies form 1 KV to 2 KV maintaining current up to 15 mA. Argon and helium gases are used as background gases in the glass chamber. Experiments are carried out with different cathode-anode configurations at different background pressures. Turbo pumps and needle valves are used to control the gas pressure inside the glass chamber respectively. For transmitting microwave a horn antenna is fixed at the flange of one of the ports of glass chamber and properly aligned according to the position of plasma column and MPC. Flange of the second port of glass chamber is used to take the electrical connections between power supplies and electrodes. For receiving the transmitted microwave power, another horn antenna is fixed on a stand outside the glass chamber. Such horn antenna can be moved on the angle chart form +90^0 to -90^0. Microwave is fed to the transmitting antenna using microwave generator and receiving antenna is fitted to a spectrum analyzer. Transmitter, MPC and plasma column are arranged in a glass chamber in such a way that the experiments can be carried out for different positions of plasma column.

Cuts-off density for 18 GHz frequency

$$n_c = 1.24\times10^{4}\times\{f(MHz)\}^{1/2}\ cm^{-3} \qquad n_c = 4\times10^{12}cm^{-3}\ \text{for}\ f = 18GHz$$

At low working pressure (up to 100 Torr)

$$\omega(1.13\times10^{11}) >> \nu_m(3\times10^{10})$$ Collisionless plasma for 18 GHz

At high working pressure (up to atmospheric pressure 760 Torr)

$$\upsilon_m(5\times10^{11}) \geq \omega(1\times10^{11})$$ Collisional plasma for 18 GHz

For collisionless plasma of density 5 X 10^{12} cm^{-3} at working pressure 10 Torr

Electric conductivity of plasma, $$\sigma = 2.82\times10^{-4}\times\frac{n_e}{\omega^2}\upsilon_m$$

$$\sigma = 1.1\times10^{-3}\,Ohm^{-1}.Cm^{-1}$$

Skin depth in given plasma for 18 GHz

$$\delta = \frac{5.03}{\{\sigma(Ohm^{-1}.cm^{-1}).f(MHz)\}^{\frac{1}{2}}}cm$$

$$\delta = 11\ \text{mm for}\ f = 18\ \text{GHz}$$

Fig. 5. Calculations for plasma parameters

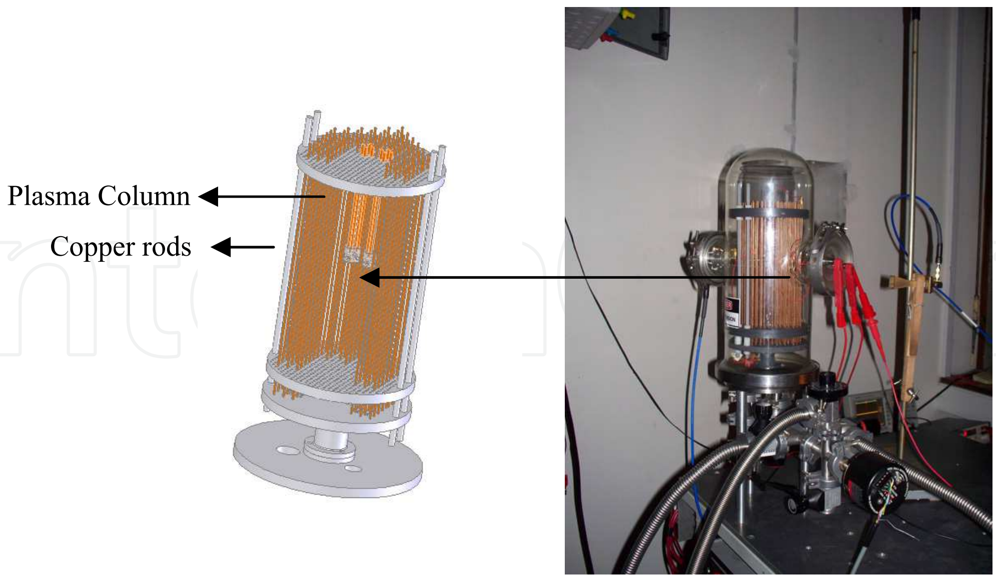

Fig. 6. A photo of experimental set up for plasma added MPC

5.3 Measurements and results

Experiments are carried out to study the electromagnetic bands gaps (EBGs) of X-band microwave through different configurations of triangle structure of MPC with and without plasma columns. Measurement method is shown in Fig.7.

5.3.1 Without and with plasma in central default

It has been studied that flat and forbidden bands at 18 GHz can be formed by MPC and defaulted MPC (Kumar 2011a, Kumar 2011b). Although this research work has potential to improve the tunability of PCs, it seems that enhancement in the tunability and controllability in this MPC is required because for tuning the MPC one needs to physically remove the metallic rods by mechanical effort (Kumar 2011a). For this concern, attention is paid to use a plasma column in the hole or default of MPC because plasma can be created and destroyed by switching ON and OFF. With the help of this approach, tunability of MPC can be increased as rapidly as the plasma can be formed and destroyed.

Hence experiments are carried out to measure the transmitted power at 18 GHz through MPC with and without plasma column. For this purpose electrodes of separation 20 mm are kept at the centre hole and well connected with the power-supplies. Finally, a plasma column of density of 5 x 10^{12} cm^{-3} and electron temperature of 2eV is formed around atmospheric pressure. Transmitted power of microwave is measured at different angles. Plasma is characterized [Kumar 2009b] as a collisional medium, which shows cut-off for 18 GHz microwave. A schematic of measurement method with electrode and with plasma in electrodes is shown in Fig. 8 (a) and (b) respectively.

Measurements of transmitted power of 18 GHz with electrodes and with plasma column are presented in Fig.9. Results of this figure show that transmitted power –38dBm at + 45^0 for electrodes at the separation of 20 mm are fixed and transmitted power becomes –48 dBm when plasma is formed between electrodes. Negative and positive refraction is also studied by forming the plasma in the left side and the right side default from the centre in front row. Hence by switching ON and OFF the plasma, flat and forbidden bands can be achieved at 45^0. Due to these strong evidences, it can be concluded that tunability and controllability of MPC over the PCs and PPCs can be enhanced by using a plasma column in a MPC.

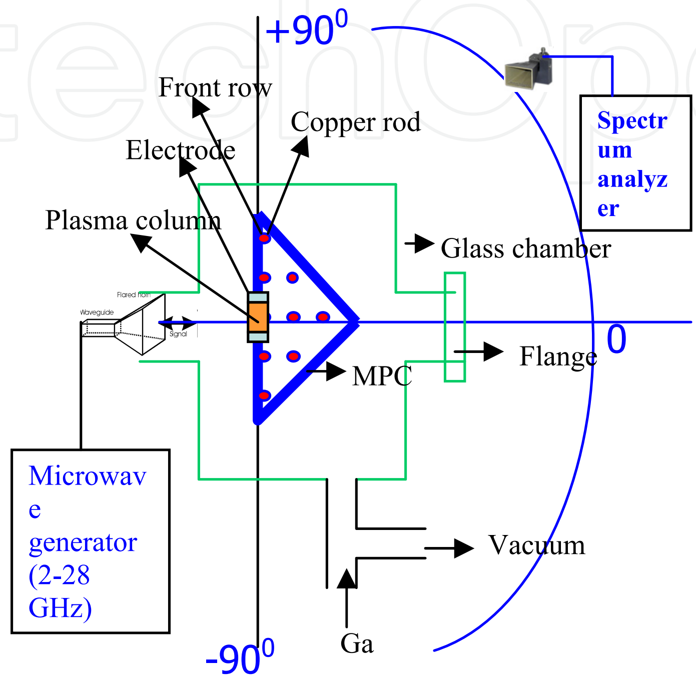

Fig. 7. A schematic diagram of measurement method showing MPC in triangular shape inside a glass chamber for measuring microwave transmission through MPC with and without plasma columns.

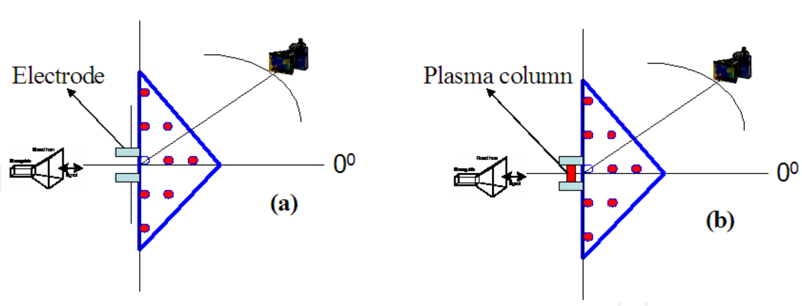

Fig. 8. (a) Measurement method of transmission of 18 GHz with electrode only (b) with plasma column at the central default of MPC.

So far, it has been successfully demonstrated how forbidden bands and flat bands can be formed by hybrid plasma photonic crystal. Although this study reveals importance and applications of plasma to control the microwave propagation in PCs, some minor problems are realized during the experiment e.g. adjustment of the electrodes, initiation of breakdown for discharge and sustaining plasma for long time because plasma column is formed inside the MPC where it is surrounded by metallic rods, which creates capacitive effects. Here it may be quite interesting to use plasma column between transmitter and MPC. Hence in the next section, attention is paid to the study of microwave propagation when plasma column is formed between transmitter and front row of MPC.

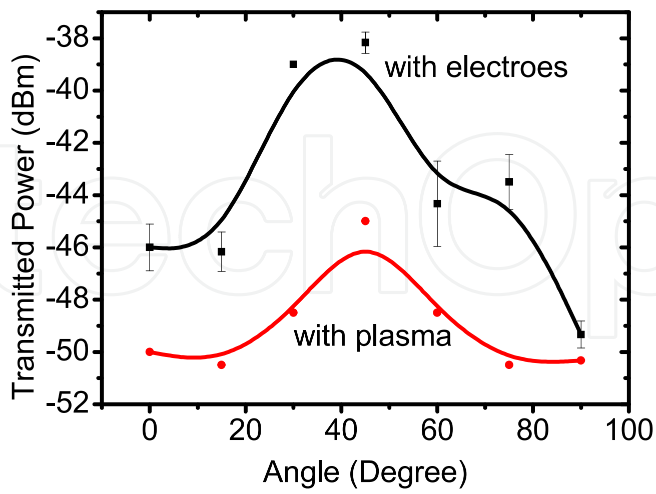

Fig. 9. Variation in the microwave transmitted power at different angles with electrodes only and plasma column within electrodes at the centre hole or default.

5.3.2 Plasma column between transmitter and metallic photonic crystal

In this experiment, a plasma column of density around 10^{12} cm^{-3} is formed at 40 mm to 100 mm away from the MPC and transmitted power of microwave is measured at different angles. Measurements with and without plasma column are presented in Fig.10. Findings of this study suggest that transmitted power is –50dBm (forbidden band) at every angle around MPC when there is no plasma column within electrodes of separation 15 mm. When plasma is formed between electrodes, transmitted power –35 dBm (flat band) is received at $+45^0$. Thus, negative refraction can also be controlled using plasma column. During this experiment it is also noticed that when the plasma column is situated between 70 mm to 100 mm away from the front row of MPC towards the transmitter, flats bands are measured and if plasma column is situated at a distance of 10 mm to 40 mm from front row of MPC, forbidden bands are measured at same angle. With this experiment, it can also be pointed out that position of plasma column can also control the propagation of microwave.

6. Conclusion

Negative refraction by the photonic crystal has been achieved for microwave to optical range. Plasma photonic crystals are used to enhance the controllability and tunabelity of microwave propagation. Plasma crystals can be also used for microwave to terahertz frequency filter. However plasma in metallic photonic crystal is a suitable technique to control the microwave in such a way that negative and positive refraction can be achieved. For this purpose micro-discharged mechanism is used to form plasma column at atmospheric pressure in a metallic photonic crystal. Argon, helium, xenon and their mixtures are used as a background gas. Transmitter, MPC and plasma column are arranged in a glass chamber in such way that the experiments can be carried out for different positions of plasma columns. A 20 mm long plasma column of electron density around 10^{13} cm^{-3} is formed. Experiments are conducted to study the electromagnetic band gaps of X-band microwave through different configurations of triangular MPC with and without plasma column. Transmitted power of 18 GHz with electrodes (without plasma between electrodes) and with plasma in electrodes are measured. Results reveal that transmitted power of – 38 dBm is received at + 45^0 for electrodes at a separation of 20 mm which becomes -48 dBm when plasma is formed between electrodes. In another experiment, a plasma column is formed between MPC and transmitter and transmitted power is measured for every angle. Findings of the study suggest that when plasma column of length 15 mm is formed in electrodes, which are fixed 70 mm to 100 mm away from the MPC, flat band of power level -35 dBm is received at + 45^0 while forbidden band of power level – 50 dBm is noticed when plasma column is formed at a diastase of 10 mm to 40 mm from the MPC.

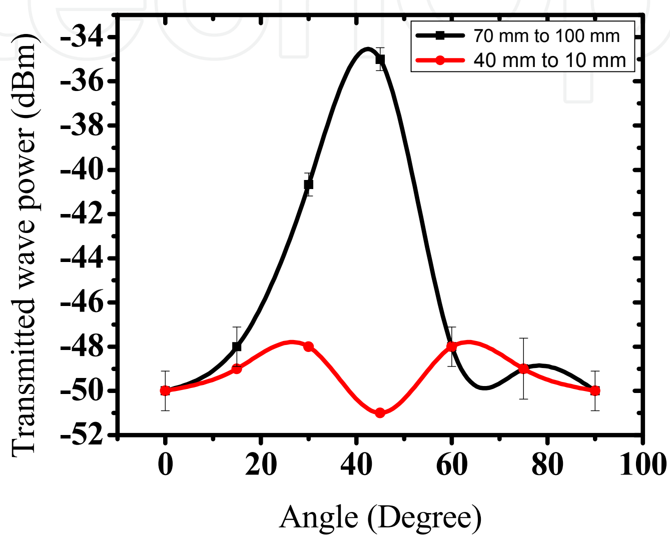

Fig. 10. Variations in the transmitted microwave power at different angles in the presence of plasma column at different places in between transmitter and metallic photonic crystal.

Therefore, by switching ON and OFF the plasma column, propagation of microwave in metallic photonic crystal can be controlled in such a way that positive and negative refraction can be achieved. This chapter can be concluded from the fact that plasma can be used to form tunable / controllable photonic crystals.

7. Acknowledgment

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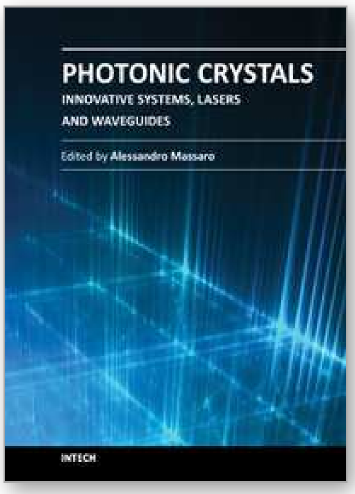

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The second volume of the book concerns the characterization approach of photonic crystals, photonic crystal lasers, photonic crystal waveguides and plasmonics including the introduction of innovative systems and materials. Photonic crystal materials promises to enable all-optical computer circuits and could also be used to make ultra low-power light sources. Researchers have studied lasers from microscopic cavities in photonic crystals that act as reflectors to intensify the collisions between photons and atoms that lead to lazing, but these lasers have been optically-pumped, meaning they are driven by other lasers. Moreover, the physical principles behind the phenomenon of slow light in photonic crystal waveguides, as well as their practical limitations, are discussed. This includes the nature of slow light propagation, its bandwidth limitation, coupling of modes and particular kind terminating photonic crystals with metal surfaces allowing to propagate in surface plasmon-polariton waves. The goal of the second volume is to provide an overview about the listed issues.

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