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# Design of an ITO Based CNT Coated Transparent Nano Patch Antenna Assisted by Characteristic Mode Analysis

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***Abstract*—An Indium-doped Tin Oxide (ITO) based optically transparent nano-antenna is presented in this paper. E-shaped patch is used to resonate at 0.76 THz. Despite of high fractional bandwidth, the radiation efficiency as well as gain of the ITO based antennas are low due to high resistivity and low conductivity of ITO thin films. To overcome this limitation, carbon nano tube (CNT) is used as cover over radiating patch of the proposed antenna. As a result, due to high conductivity of CNT, along with gain and efficiency, the fractional bandwidth of the proposed antenna is also increased. Characteristic mode analysis (CMA) is carried out to provide more insightful physical characteristics of the proposed antenna. It helps to understand the structural optimization and to determine the operating frequency. Moreover, a copper based non-transparent E-shaped patch antenna, resonated at 0.76 THz is also designed to compare with the proposed antenna. The proposed antenna has fractional bandwidth of 21% which is much better than conventional patch antenna and some previous transparent antennas. A peak gain of 4.9 dBi is obtained at 0.76 THz with good radiation performance. The designed antenna is suitable for satellite communication because of its broad bandwidth, reasonable radiation efficiency, sufficient gain, light weight and compactness.**

***Keywords—ITO, CNT, Nano-antenna, E-shaped, CMA Transparent Antenna***

## I. INTRODUCTION

Conventional antennas are designed by using a thick metal layer of copper or gold printed on a dielectric substrate like Teflon, FR4 or Duroid which is not transparent. Space constraints and integration of antenna with solar cell are two important factors in satellite communication [1]. If non-transparent antenna is integrated with solar cell, then the shadow of antenna will be fallen on solar cell. As a result, mismatch will be occurred in solar cell and its efficiency will be decreased. Another important thing is that, high fractional impedance bandwidth is essential for THz applications. As a result, designers are emphasized on designing optically transparent antennas to overcome these constraints as they are light in weight, compact in size and provide high fractional impedance bandwidth [2].

The root of optically transparent antennas are some see-through antennas developed in 1990's. In 1997, the first feasibility study of transparent antenna was done by R.N. Simons and R.Q. Lee [3]. Optically transparent monopole antennas characteristics were also studied and investigated [4]. More recently ITO and fluorine doped tin oxide (FTO) based U-shaped and E-shaped antennas performances have been analyzed and compared [5], [6]. Since the beginning to till date, transparent antennas of different shaped are designed. Such antennas are being reported for their use in applications such as wireless access point, energy harvesting, ultra wideband applications and automobiles applications. There are many types of impurity doped metal oxide like ITO, FTO, titanium doped indium oxide (TIO), gallium zinc oxide (GZO), and antimony tin oxide (ATO). At present, among these impurity doped metal oxide, ITO has been broadly utilized as transparent conductive electrode in optoelectronic devices and industrial applications [7].

ITO is an n-typed degenerated semi-conductor with wide band gap of approximately 3.5 eV [8]. ITO is mainly considered for its best optimization between electrical conductivity and optical transmittance. Deposition method of ITO includes chemical methods like spray-hydrolysis, sol-gel process and physical methods like rf. Sputtering, pulse lased deposition, dc magnetrons sputtering.

In case of transparent conducting oxide materials, the electrical conductivity of the film increases with the increase of film thickness but this causes decrease of transmittance. Due to increase of electrical conductivity, the antenna's radiation efficiency is increased too and vice-versa. Therefore, a compromise must be made between optical transmittance of the film and the radiation efficiency it offers to the antenna. Electrical conductivity of 2.88×105 S/m and optical transmittance more than 80% are reported in [9], [10]. One of the best recently developed antenna transparent material is carbon nano tubes (CNT). CNTs are tubes of carbon particles in molecular scale with special characteristics. These properties include stiffness, strength along with other unique electronic characteristics. More precious information on CNTs is available in [11]. Researchers found that it can be connected to opto-electronic devices as transparent conductive electrodes [12].

CMA is a characteristic mode theory (CMT) based source free technique of analyzing the resonant characteristics of arbitrary radiating structure. The resonant frequency of fundamental mode along with other higher order modes can be obtained by CMA. These important modal analysis results indicate how to excite the electromagnetic structure for obtaining desired radiation pattern at a definite frequency. CMT was first proposed by Garbacz in 1962 and further works on it were carried out by Mautz and Harrington [13], [14]. The theoretical background of CMA is described elaborately in [15]. The recent development, implementation and application of it is described in [16].

In this paper, a transparent nano-antenna resonate at 0.76 THz by employing ITO is presented. The antenna consists of an E-shaped patch optimized by CMA. A CNT coating is placed above the patch to enhance the performance of the antenna. Design and performance of the proposed antenna along with detail CMA analysis are demonstrated in the following sections.

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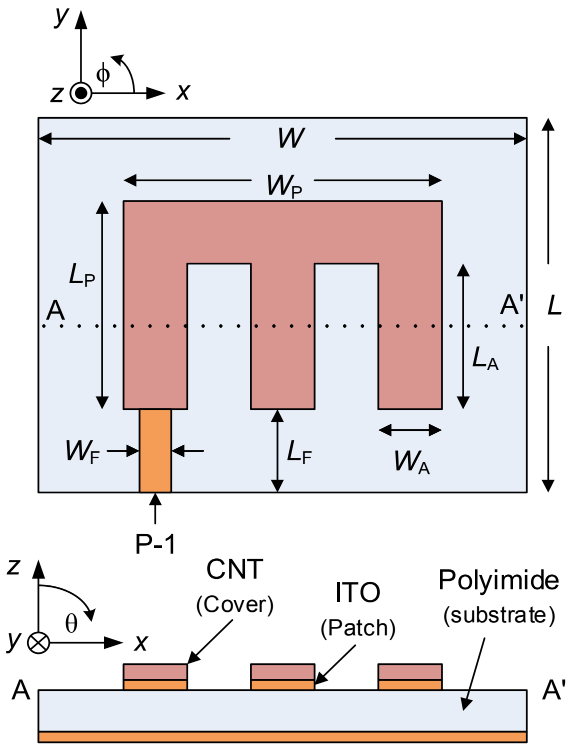


Fig. 1. Schematic layout and cross-sectional view (AA') of the proposed E-shaped antenna.

## II. DESIGN OF THE PROPOSED ANTENNA

Fig. 1 shows the schematic layout and cross-sectional view (AA') of the proposed transparent antenna. A newly configured E-shaped antenna for terahertz (THz) applications is introduced here. The antenna dimensions are calculated by the equations mention in [5] and studied by CMA to find out exact resonant characteristics. This analysis helps to get the best possible performance from the antenna. ITO based thin film is used to design ground and patch of the antenna. On the other hand, for comparison purpose, a non-transparent copper material is used to configure the patch and ground plane of the copper based antenna. Both of the antennas are covered with a thin layer of CNT to improve their radiation characteristics.

An E-shaped patch of ITO, having a thickness of 0.4 µm, is placed on a 20 µm thick transparent polyimide substrate of dielectric permittivity of 3.5 and loss tangent of 0.008. The length ($L_P$) and width ($W_P$) of the E-shaped patch are 88.98 µm and 133.2 µm, respectively. The length ($L_A$) and width ($W_A$) of the three arms of the E-shaped structure are equal and they are 76.8 um and 35.5 um, respectively. The length ($L$) and width ($W$) of the substrate are 208.98 µm and 433.2 µm, respectively. The length and width of the ground are as same as substrate. A 0.4 µm thick ITO thin film is used as ground. A feed line with a length ($L_f$) of 60 µm and width ($W_f$) of 10 µm is used to excite the patch using a port, P-1. The dimensions of the both ITO based transparent antenna and Cu based non-transparent antenna are same. Due to high conductivity along with transparent nature of CNT, both the antennas are covered with a thin layer of CNT with a thickness of 3.4 µm to improve their radiation performances. The shape and dimension of the CNT layer are kept exactly same as E-shaped patch.

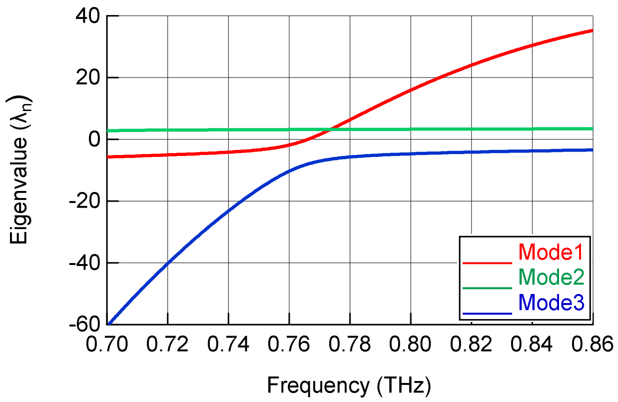


Fig. 2. Eigenvalue ($\lambda_n$) curve of the proposed E-shaped transparent antenna.

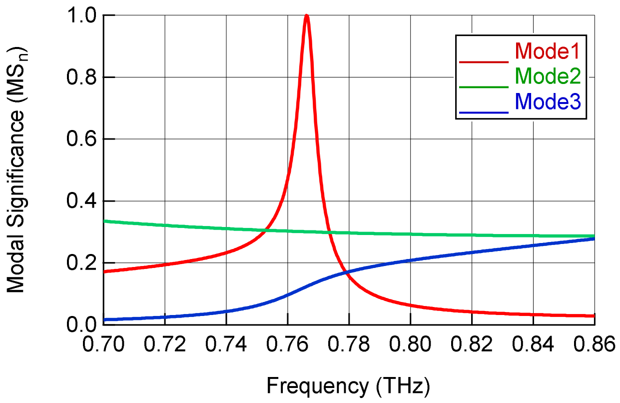


Fig. 3. Modal significance ($MS_n$) curve of the proposed E-shaped transparent antenna.

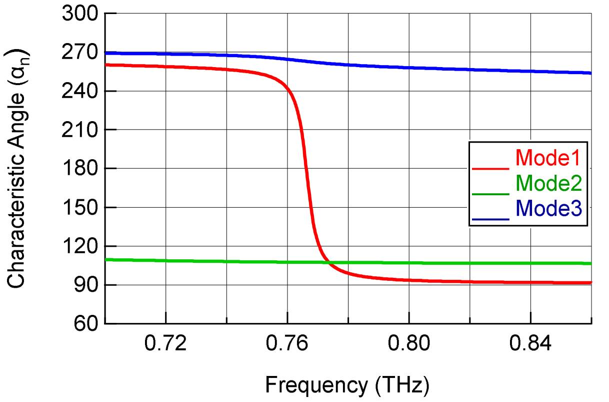


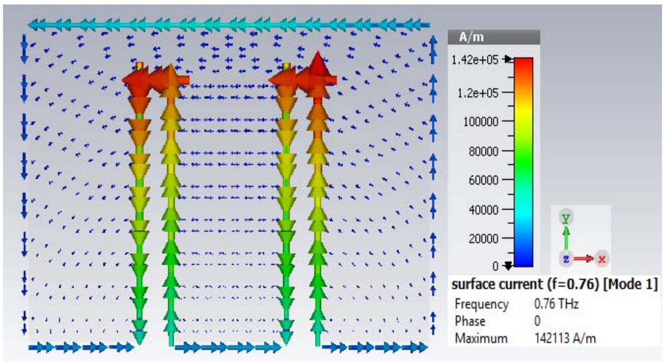
Fig. 4. Characteristic angle ($\alpha_n$) curve of the proposed E-shaped transparent antenna.

## III. CHARACTERISTIC MODE ANALYSIS

Characteristic modes also known as current modes for arbitrarily shaped radiating bodies are obtained by solving the following eigenvalue equation

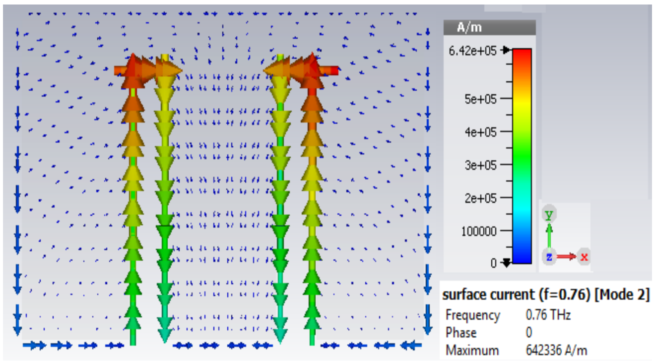
$$X(\bar{J}_n) = \lambda_n R(\bar{J}_n)$$

Where $\bar{J}_n$ are Eigenfunctions, $\lambda_n$ are eigenvalues, $R$ and $X$ are real and imaginary parts of method-of-moments impedance operator $Z = R + jX$. For designing the proposed antenna, only three parameters namely eigenvalue ($\lambda_n$), modal significance ($MS_n$) and characteristic angle ($\alpha_n$) are need to be considered.



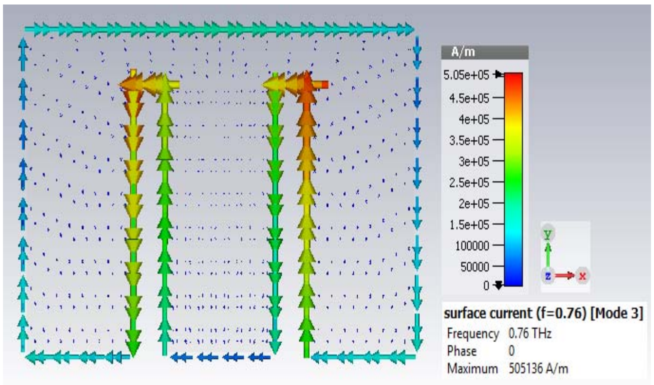
surface current (f=0.76) [Mode 1]
Frequency 0.76 THz
Phase 0
Maximum 142113 A/m

Fig. 5. Surface Current Distribution Curve (Mode 1) of the proposed E-shaped transparent antenna at 0.76 THz.



surface current (f=0.76) [Mode 2]
Frequency 0.76 THz
Phase 0
Maximum 642336 A/m

Fig. 6. Surface Current Distribution Curve (Mode 2) of the proposed E-shaped transparent antenna at 0.76 THz.



surface current (f=0.76) [Mode 3]
Frequency 0.76 THz
Phase 0
Maximum 505136 A/m

Fig. 7. Surface Current Distribution Curve (Mode 3) of the proposed E-shaped transparent antenna at 0.76 THz.

### A. *Eigenvalue Analysis*

Eigenvalues $\lambda_n$ vary from $-\infty$ to $\infty$. The magnitude of a certain eigenvalue illustrates how efficiently the characteristic mode radiates. The mode is a good radiator when eigenvalue $\lambda_n$ is zero. The first three eigenvalues are depicted in fig. 2. It is seen that eigenvalue corresponds to mode 1, $\lambda_0$ starts from the negative side, then cross the zero level line and continues to increase further in the positive side. So, at the point of zero crossing, $\lambda_0$ is zero which means that at that moments the mode reached to resonance state and acts as a good radiator.

From the figure it is also seen that at that time the resonant frequency is nearly 0.76 THz. On the other hand eigenvalue corresponds to mode 2, $\lambda_1$ always holds a positive value and never cross the zero level. As a result it will never reach to resonance condition and only contributes to increase the reactive magnetic energy of the antenna. Similarly eigenvalue corresponds to mode 3, $\lambda_2$ always holds a negative value and will never cross the zero level and contribute to increase the electrical energy of the antenna.

### B. *Modal Significance Analysis*

To describe the characteristics mode, another parameter named modal significance ($MS_n$) is put forward over eigenvalues, which is defined by

$$MS_n = \left|\frac{1}{1+j\lambda_n}\right|$$

Modal significance of the first three mode of the proposed antenna is depicted in fig. 3. A mode meets the resonance condition when the value of $MS_n = 1$. From the figure it is seen that only mode 1 reached the value 1 nearly 0.76 THz and other modes aren't. As a result only mode 1 effectively contributes to the total radiation of the designed antenna when a source is applied.

### C. *Characteristic Angle Analysis*

The operation of the antenna can also be explained by another parameter namely characteristic angle ($\alpha_n$). It illustrates the phase difference between the characteristic current $\bar{J}_n$ and its associated characteristic field $\bar{E}_n$ and defined by $\alpha_n = 180° - \tan^{-1}(\lambda_n)$. When $\alpha_n = 180°$, the modes are at resonance and the structure radiates strongly at that frequency. However the modes with $\alpha_n = 90°$ or $270°$ radiates poorly. From the fig. 4, it is evident that mode 1 cross the 180° line at nearly 0.76 THz i.e. this is the center frequency of the antenna and at this frequency the antenna will act as good radiator. However mode 2 and mode 3 will never cross the 180° line and radiate poorly. Mode 2 operates nearly 105° and mode 3 operates at 270° which means that these two modes mainly stores magnetic and electrical energy, respectively.

### D. *Surface Current Analysis*

The almost uniform surface current distribution at mode 1 compared to mode 2 and mode 3 as showed in figs. 5-7 reveals that the antenna will act as a good radiator at mode 1.From the above discussion, it can be said that the proposed antenna will operate at mode 1 and radiate excellently at center frequency of 0.76 THz.

## IV. RESULTS AND DISCUSSIONS

The Proposed antenna is simulated by using CST MW Studio. The $S_{11}$ and radiation characteristics are investigated in 0.70–0.86 THz band. Fig. 8 illustrates the reflection coefficient of proposed E-shaped transparent antenna and Cu Based non transparent antenna. For the proposed antenna, it is seen that at resonant frequency of 0.76 THz, a reflection coefficient of 43 dB is achieved with excellent wide fractional bandwidth of 21%. The figure indicates a good impedance matching of the antenna. While for the Cu based antenna at resonance frequency of 0.76 THz, a reflection coefficient of 16 dB is achieved with fractional bandwidth of 9%.

Fig. 9 shows the radiation efficiency of the proposed antenna and Cu based non transparent antenna. For the proposed antenna radiation efficiency of 48% is observed at

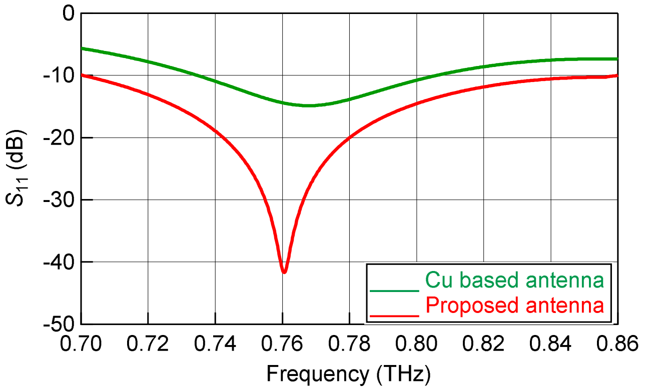


Fig. 8. $S_{11}$ of the proposed E-shaped transparent antenna and Cu based non-transparent antenna.

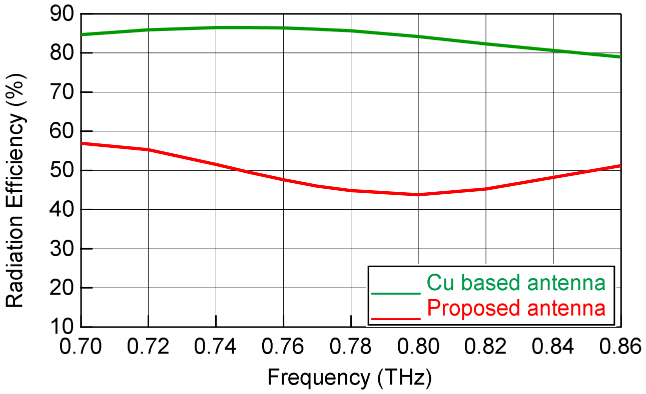


Fig. 9. Radiation efficiency of the proposed E-shaped transparent nano-antenna and Cu based non-transparent antenna.

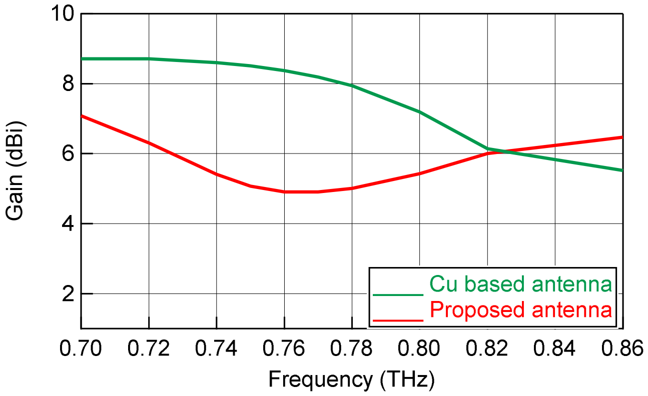


Fig. 10. Gain of the proposed E-shaped transparent nano-antenna and Cu based non-transparent antenna.

resonant frequency. At 0.70 THz, the radiation efficiency of about 57% is obtained which is very much desired. While for the Cu based antenna at resonant frequency of 0.76 THz, radiation efficiency of 88% is observed. This difference in radiation efficiency is due to the high resistivity of ITO thin film than Cu.

Fig. 10 shows the gain of the antenna with respect to the frequency and fine overall gain of more than 4.9 dBi is obtained over the desired band for the proposed antenna. While for the Cu based antenna, the overall gain of more than 7.1 dBi is obtained.

It is seen that, the radiation efficiency as well as overall gain of the Cu based non-transparent antenna is higher than proposed antenna. But it is the transparency and wide fractional bandwidth which made the proposed antenna more suitable in THz application especially for satellite application than Cu based non- transparent antenna.

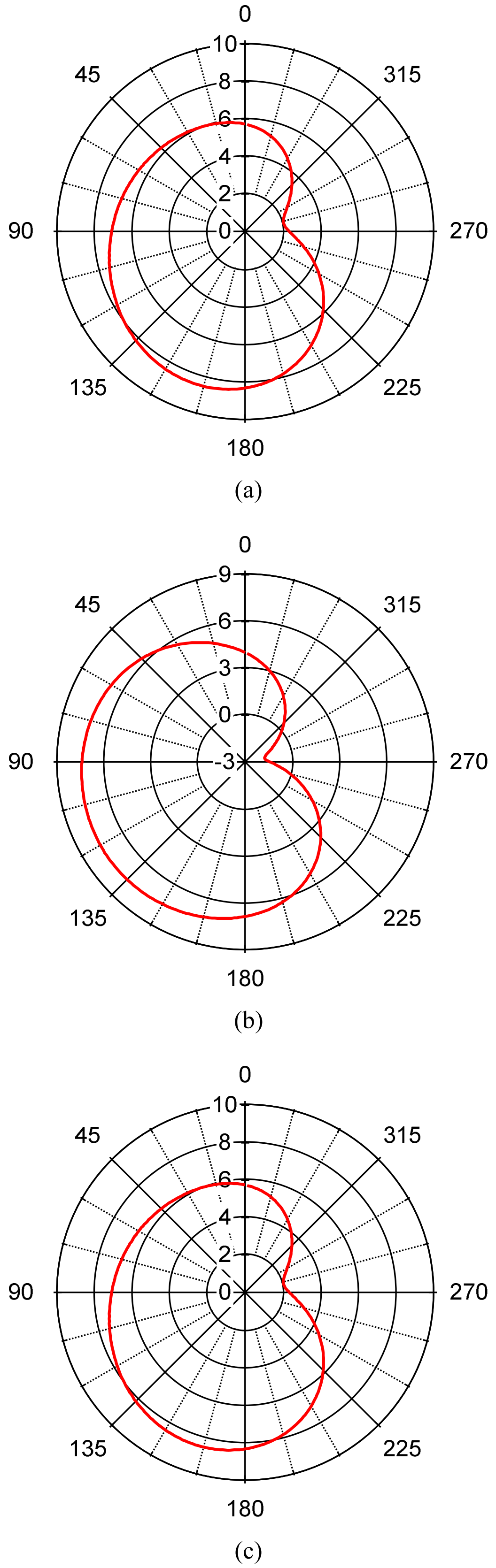


Fig. 11. Far field radiation pattern of the proposed antenna; (a) 0.72 THz (b) 0.76 THz (c) 0.80 THz.

Fig. 11 illustrates the radiation pattern of the proposed antenna at 0.72 THz, 0.76 THz, and 0.80 THz. From the figure, it is seen that at three different frequencies, good radiation performances are obtained that indicates the designed antenna can show excellent performance over whole impedance bandwidth.

TABLE I. PERFORMANCE COMPARISON OF PROPOSED ANTENNA AND OTHER PREVIOUS WORKS

| **Parameter** | **Optically Transparent Antenna** | | | | **Non Transparent antenna** |
|---|---|---|---|---|---|
| | ***[5]*** | ***[5]*** | ***[6]*** | ***Proposed*** | |
| Patch Material | ITO | FTO | ITO | CNT coated ITO | Cu |
| Resonant Frequency (THz) | 0.75 | 0.75 | 0.75 | 0.76 | 0.76 |
| Radiation efficiency (%) | 41 | 32 | 41 | 48 | 88 |
| Directivity (dBi) | 7.22 | 7.06 | - | 7.7 | 7.6 |
| Gain (dBi) | 3.31 | 2.1 | 3.9 | 4.9 | 7.1 |
| 10 dB Impedance Bandwidth (%) | 9.54 | 11.49 | 11.73 | 21 | 9 |

The most important achievement of the proposed design is that over the entire band of interest, the gain of greater than 4.9 dBi and maximum gain of 7.1 dBi are achieved. Another important factor of transparent antenna is fractional bandwidth. A fractional bandwidth of 21% is obtained which is much higher than fractional bandwidth of reference case [5], [6] and Cu based non transparent antenna as shown in Table I. The minimum radiation efficiency of 43% and maximum 57% is achieved in proposed antenna which is also better than the radiation efficiency of [5], [6]. Therefore, it is evident that the proposed antenna gives better performances than other reported transparent antenna. The overall performances of the proposed antenna are improved for using CNT coating.

## V. CONCLUSION

An optically transparent antenna using CNT coated ITO conducting thin film operated in THz region has been proposed. The antenna has been investigated using CMA to get optimum performance. Gain is more than 4.9 dBi over whole operating bandwidth which is better than other similar kind of transparent antenna. The Cu based non transparent antenna has a narrow bandwidth of less than 9% where the proposed transparent antenna has a bandwidth of 21% which is even much larger than E-shaped and U-shaped antennas, reported previously. Such broad bandwidth is most significant for employing the THz antenna in satellite to satellite communication and screen of concealed objects in advanced recognition system.

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