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Investigation of Plasmonic Metal Conductors and Dielectric Substrates on Nano-Antenna for Optical Wireless Communication

Kavitha S*, Kanduri V. S. S. S. S. Sairam, and Ashish Singh

Abstract—In this manuscript, plasmonic metal conductors such as Silver, Gold, Aluminum, Copper, Chromium, Tungsten, Titanium, and Nickel are investigated on a T-shaped Nano dipole antenna using dielectric materials such as Silicon Dioxide, Zinc Oxide, Indium Tin Oxide, and Silicon Nitride. The optical properties of the conductors and dielectric materials are modeled using Drude and Lorentz dispersive models, respectively. It is observed that the Aluminium metal supports high quality plasmonic oscillations for a wide range of Terahertz frequencies. The Aluminium metal also shows high losses occurring at the Terahertz frequency among the other metals. The Gold and Silver can resonate in the visible region and have moderate losses compared to the other plasmonic metals. It is noticed that the near-zero permittivity point of the Silicon Dioxide substrate occurs at 2875 THz which is much greater than the other three substrates. Further, it is observed that on the Silicon Dioxide, Zinc Oxide, and Silicon Nitride substrates the Silver Nano dipole antenna shows the maximum directivity of 6.615 dBi, 5.671 dBi, and 5.709 dBi, respectively. The Aluminium Nano-antenna gives the maximum directivity of 5.066 dBi on the Indium Tin Oxide substrate. The Silver-Silicon Dioxide Nano-antenna will be suitable for the terahertz optical wireless communication.

1. INTRODUCTION

Nano/optical antenna is a Nano-sized device capable of enhancing field to a large extent at the Terahertz (THz) frequency [1–3]. This structure comprises a conducting optical metal surface on a dielectric substrate and produces plasmonic oscillation when it is excited via optical source, and it is referred as plasmonic antenna. In contrast to the Radio Frequency (RF) antennas, plasmonic antennas resonate in the optical frequency region due to which novel materials are used in the design of antenna structure. Nano-antennas are used in optical wireless communication, biomedical sensing, and energy harvesting [4–8] applications. These antennas are becoming popular recently with the advances in the field of plasma science, nanotechnology, emerging quantum electronics, and communication systems.

The characteristics of a plasmonic antenna depend on the optical and chemical properties of the design materials. The material properties such as permittivity and permeability play an important role in the antenna behavior. The permittivity of the material is frequency-dependent and contains real and imaginary parts at the THz frequency. The conducting material of the plasmonic antenna must exhibit real negative permittivity to support plasmonic oscillations [9], and imaginary part of the permittivity signifies the losses occurring at the THz frequency [10]. Conventionally, Gold and Silver are popular among plasmonic metal conductors even though they exhibit high losses at the THz frequency [11, 12]. These Nanostructures are expensive and radiate nearly visible frequency range only. These facts have motivated the researchers to use other plasmonic metals for the THz Nano-antenna design. The other plasmonic metals such as Aluminium can support plasmonic oscillation in the Ultra Violet (UV) frequency region [11]. Copper is another good choice as it supports plasmonic

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oscillations like Gold and Silver, and it is economical too. Morshed et al. showed that Chromium and Tungsten antennas can handle power dissipation more than the Gold Nanostructures [13]. Mironov et al. demonstrated that the Titanium Nano-antenna can handle power more than the Gold Nano-antennas [14]. Ma and Vandenbosch studied the performance of the metal conductors on the Nano-antenna in terms of impedance and radiation efficiency [4]. The difficulties involved in the fabrication process restrict the use of these metals compared to the Gold and Silver in Nano-antenna structure design [15, 16].

Another important parameter in Nano-antenna design is the selection of an appropriate dielectric substrate for the design. The optical properties of a dielectric substrate will affect the performance of the Nano-antenna significantly. For the THz Nano-antenna design traditionally semiconductors are used as a dielectric substrate [10]. Even semiconductors show plasmonic metal behavior at high THz frequency under some conditions. This enabled the development of transparent antennas using conducting oxides [10]. Silicon dioxide substrate is more popular and is a commonly used substrate in Nano-antenna design since it is abundant and economical [17]. Silicon based antennas cannot handle high power dissipation [18] occurring in the Nanostructure. The absorption losses occurring in Nano-antenna increase the temperature, which leads to instability of the structure and also decrease in the field enhancement. Alternate substrate materials need to be investigated on the Nano-antenna to exploit the advantages of these materials. Silicon dioxide has a dielectric constant of 3.7–3.9 and band gap energy of 8.9 eV. The other semiconducting materials like Zinc Oxide has a dielectric constant of 8.1–9.3 and band gap energy of 3.37 eV. Indium Tin Oxide has a dielectric constant of 3.2 and band gap energy of 3.5–4.3 eV, and Silicon Nitride has a dielectric constant of 7.5 and band gap energy of 5 eV [17]. These novel substrates can be investigated to control the characteristics of the Nano-antenna. Dash studied the impact of Silicon substrates on the Graphene Nano patch antenna [17].

The literature shows that most of the Nano-antennas are designed using Gold and Silver metals on a Silicon dioxide substrate. Some of the works show the study of a few plasmonic metals on the Nano-antenna structure. The impact of the plasmonic metals on Nano-antenna using different substrates has not been reported for selecting the suitable metal-substrate combination. The investigation of plasmonic metals and dielectric substrates on a Nano-antenna structure is important to understanding the good metal-substrate combination to achieve the best characteristics over a desired frequency range. Based on the application metal and conductors can be selected for plasmonic Nano-antenna structure to achieve desired performance for THz radiation.

In this manuscript, the optical properties of plasmonic metal conductors such as Silver (Ag), Gold (Au), Aluminum (Al), Copper (Cu), Chromium (Cr), Tungsten (W), Titanium (Ti), and Nickel (Ni) are investigated using Drude dispersive model. Further optical properties of dielectric materials such as Silicon Dioxide (SiO_2), Zinc Oxide (ZnO), Indium Tin Oxide (ITO), and Silicon Nitride (Si_3N_4) are investigated using Lorentz dispersive model. The comparative study includes the complex permittivity and refractive index of these plasmonic materials in the THz frequency region to characterize the plasmonic Nano-antenna structure. The impact of the plasmonic conductors and substrates is investigated on the T-shaped Nano dipole antenna structure. The detailed analysis of the T-shaped Nano dipole is presented with results and discussion in the next sections.

2. T-SHAPED NANO DIPOLE ANTENNA

Figs. 1(a) and (b) depict the 2D and 3D structures of designed T-shaped Nano $\lambda/4$ dipole antenna, where W and L are the width and length of the Nano dipole antenna, respectively. The thickness of Nano dipole antenna is T. The design is simulated by considering $L = 183.5\,\text{nm}$, $W = 30\,\text{nm}$, $T = 100\,\text{nm}$, $W_1 = 10\,\text{nm}$, $L_1 = 150\,\text{nm}$, $L_2 = 60\,\text{nm}$ as shown in Fig. 1(a). The spacing of 20 nm is kept in between T-shaped Nano dipoles. The design is built on a substrate of dimension $700 \times 700 \times 150\,\text{nm}$. The impact of a substrate on the Nano-antenna design is investigated using optical substrates such as SiO_2, ZnO, ITO, and Si_3N_4. The effect of the plasmonic metals on the Nano dipole is analyzed using Ag, Au, Al, Cu, Cr, W, Ti, and Ni. The simulation is performed on CST Microwave Studio platform. Numerical analysis is performed using Finite Integration Technique (FIT) solver.

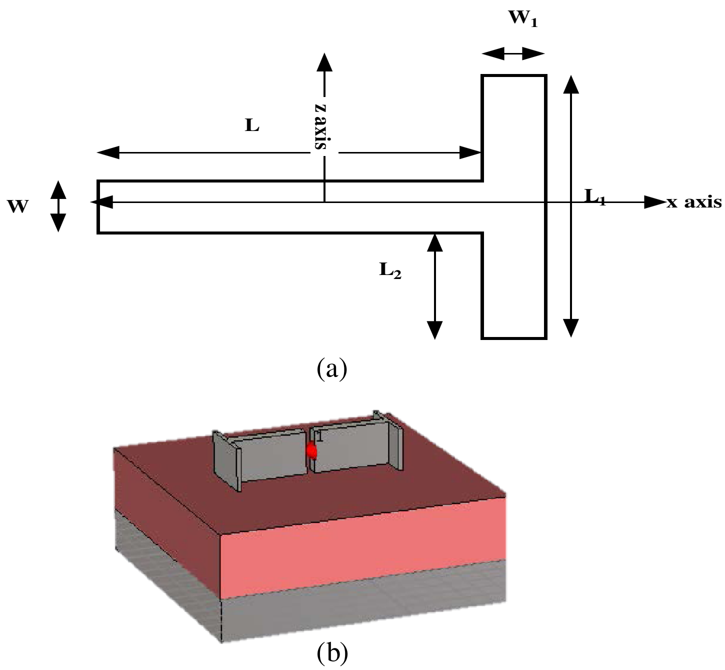


Figure 1. T-shaped Nano dipole antenna. (a) 2D view. (b) 3D view.

3. OPTICAL CHARACTERISTICS OF PLASMONIC MATERIALS

The metals and insulators are characterized by their frequency dependent complex permittivity and refractive index at optical frequency [19]. The real part of the permittivity will be negative for plasmonic materials to support Surface Plasmon Polaritons (SPP) oscillations. The imaginary part of the permittivity signifies the losses occurring at THz frequency [10]. The refractive index is the square root of the permittivity [19, 20]. The absorption and scattering behavior of the antenna at the optical frequency is proportional to the imaginary part of the refractive index. The imaginary part of the refractive index is also called as extinction coefficient [21]. Drude dispersive model includes only intra-band transitions. Generally, the conducting materials are modeled using Drude Dispersion model at THz frequency since only intra-band transitions are significant in the conductors. The semiconductors and insulators are modeled using Lorentz model [22] which includes both intra- and inter-band transitions.

Drude model [23–26]:

$$\epsilon(\omega) = \epsilon_{infinity} - \frac{\omega_{pl}^2}{\omega\left(\omega - jv_{col}\right)} \tag{1}$$

Lorentz model [23–26]:

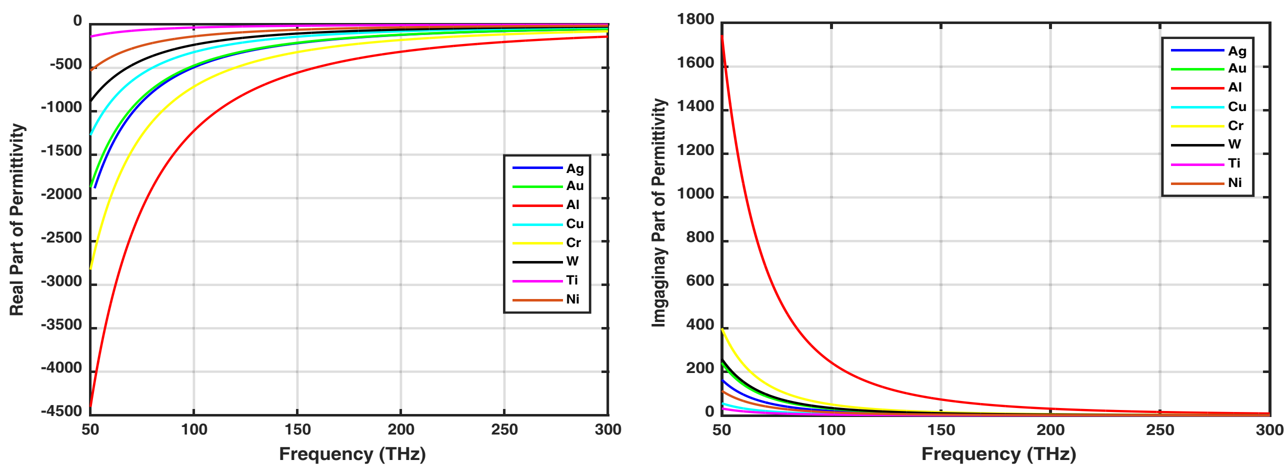
$$\epsilon(\omega) = \epsilon_{infinity} + \frac{\left(\epsilon_{static} - \epsilon_{infinity}\right)\omega_{reson}^2}{\omega_{reson}^2 + j\omega\delta - \omega^2} \tag{2}$$

where v_{col} is the collision frequency, ω_{pl} the plasma frequency, ω_{reson} the resonance frequency, δ the damping factor, ϵ_{static} the static value of permittivity, and $\epsilon_{infinity}$ the permittivity at $\omega = \infty$.

3.1. Plamonic Metals for the Optical Antenna Design

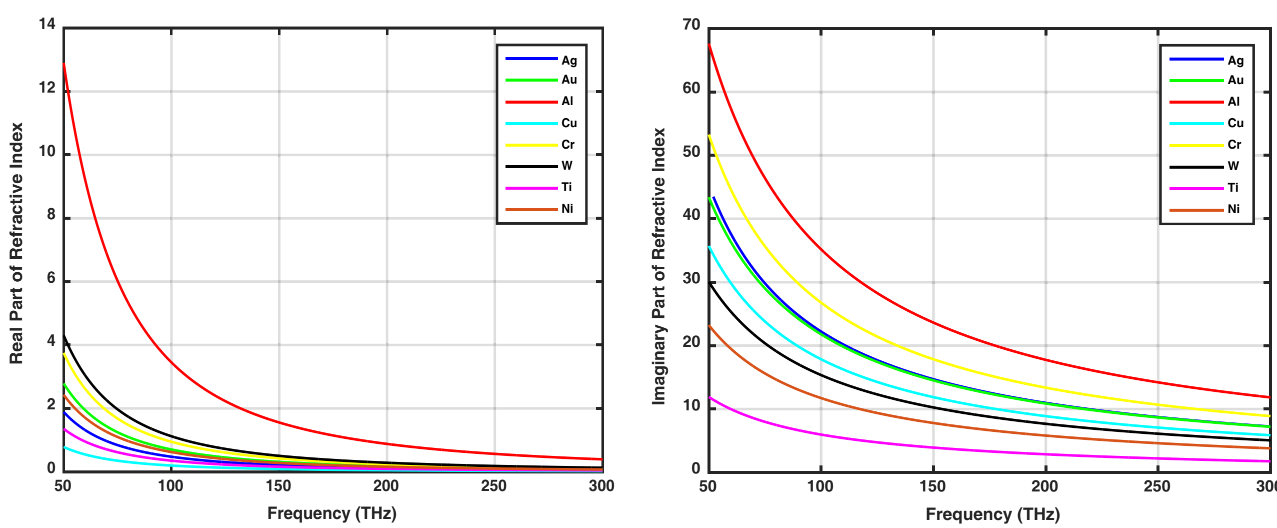
The impact of plasmonic metal conductors on the Nano-antenna is analyzed using dispersive characteristics of the metals with the help of Drude model. The investigation is performed on eight plasmonic metals Ag, Au, Al, Cu, Cr, W, Ti, and Ni. The frequency-dependent real and imaginary parts of the permittivity of these metals are depicted in Figs. 2(a) and (b), respectively. It is observed that the real part of the permittivity for all the eight conducting metals is negative at the THz frequency. This indicates that they can support SPP oscillations at the THz frequency. It is noticed that noble metals Au and Ag have almost similar values of real part of the permittivity. In comparison, metal Al has a negative real permittivity for a wide range of frequencies compared to the other metals, due to which it can be used for high THz applications, and Ti can be used for low THz applications. The imaginary part of the permittivity signifies the losses occurring in the metal [10, 19]. From Fig. 2(b) it is observed that Al has a high value of imaginary permittivity indicating high losses occurring in the metal Al even though it can support SPP very well. Although Cr is the second best in supporting SPP, it has high losses occurring at the optical frequencies. In the case of noble metals, the Ag has losses lower than that of the Au. Even though the Ti has the lowest loss, it is poor in supporting SPP. The W, Ni, and Cu metals show low losses, but they will not be so good for the propagation of SPP. The Ag and Au have optimum dispersion characteristics, and they are also chemically stable compared to the other metals. This is the reason that noble metals Ag and Au are commonly used in the Nano-antennas even though they are expensive.

The variation of real and imaginary parts of the refractive index of these metals are shown in



(a) (b)

Figure 2. Permittivity of plasmonic metals using Drude model. (a) Real part of Permittivity. (b) Imaginary part of Permittivity.



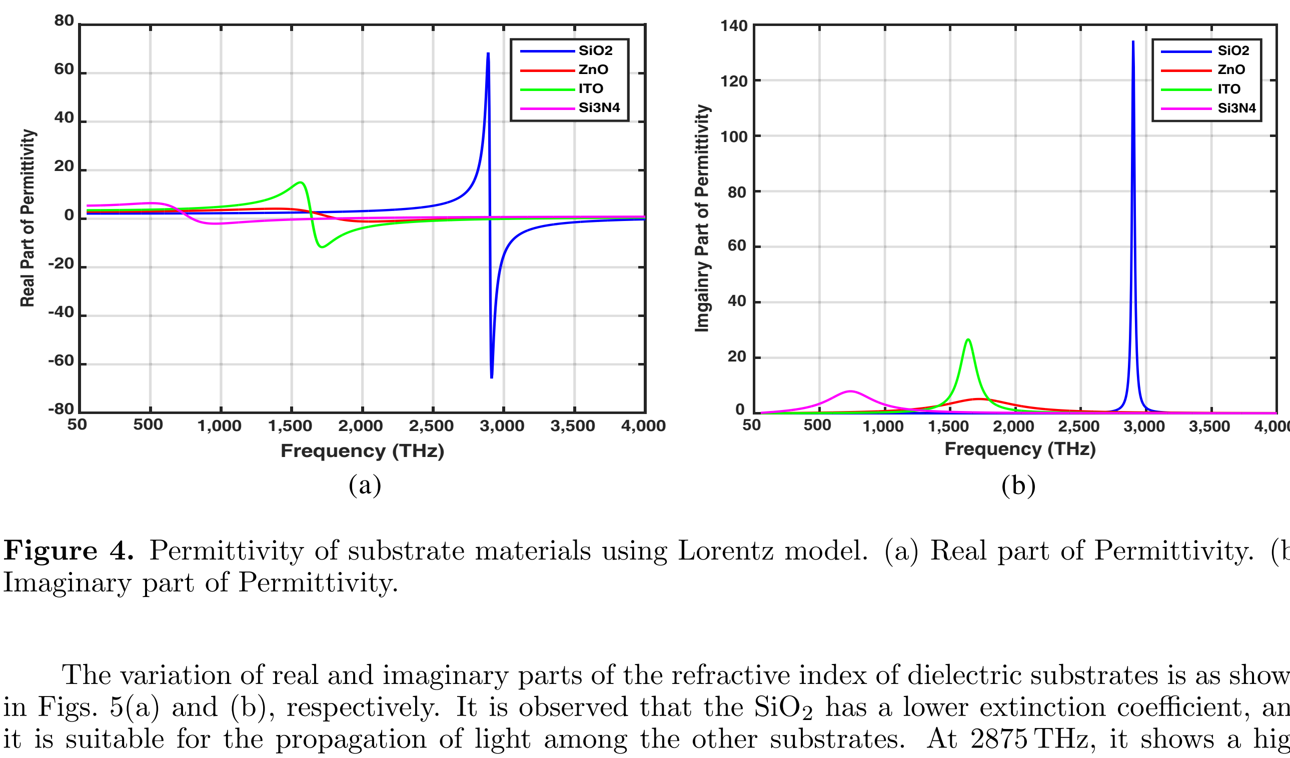
(a) (b)

Figure 3. Refractive index of plasmonic metals. (a) Real part of refractive index. (b) Imaginary part of refractive index.

Figs. 3(a) and (b), respectively. The real part of the refractive index signifies the velocity of wave propagation in the metal, and imaginary part signifies the attenuation occurring in the propagation [21]. It is observed that the Al has high extinction coefficient indicating high attenuation occurring in the Al metal. Noble metals Ag and Au have almost similar values of extinction coefficient, and the other metals, even though they have low attenuation coefficient, they are not able to support plasmonics oscillations.

3.2. Substrates for the Optical Antenna Design

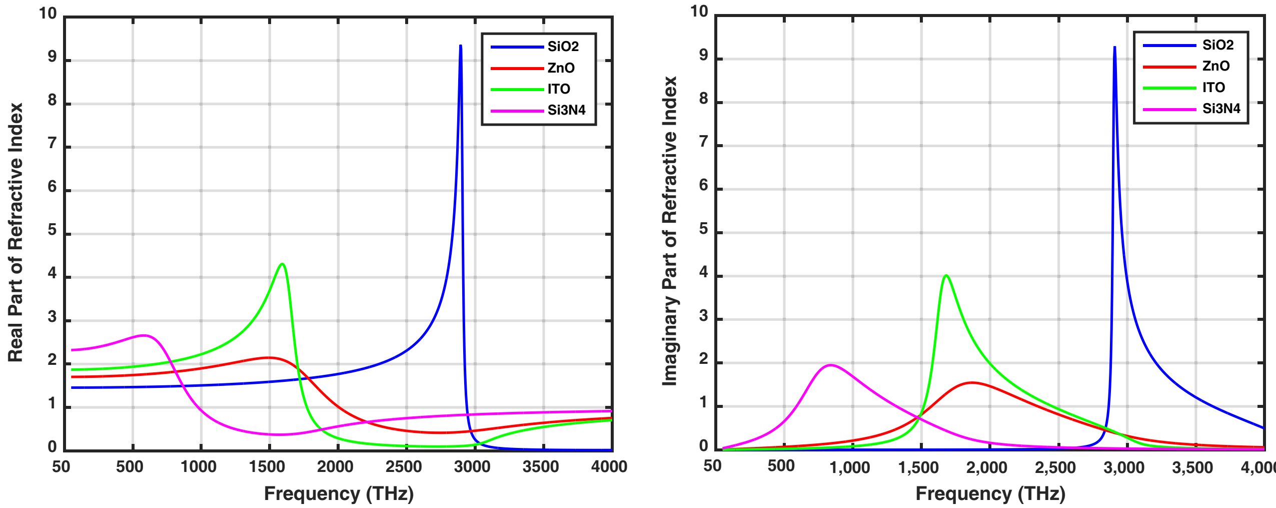
The selection of a substrate or dielectric material plays a crucial role in the Nano-antenna design and performance [17]. It is very important to choose an appropriate substrate to achieve the best Nano-antenna characteristics. In this regard, investigation is performed on four substrate materials SiO_2, ZnO, ITO, and Si_3N_4. At the THz frequency, these dielectric materials are characterized through dispersive models. For semiconductors and insulators, Lorentz model is preferable since it includes both inter and intra band transitions. Figs. 4(a) and (b) show the real and imaginary parts of the permittivity of the four substrates considered for the analysis. It is observed from Fig. 4(a) that the SiO_2 has a positive real permittivity till the frequency 2875 THz, and above this frequency it shows a negative permittivity behavior. The ZnO shows a negative permittivity behavior after 1750 THz, and ITO shows it after 1625 THz. For the Si_3N_4, this range is reduced to 750 THz. This indicates that the SiO_2 is a good substrate for the Infra-Red (IR), visible and Ultra Violet (UV) frequencies till 2875 THz. The ZnO and ITO substrates show good substrate characteristics in the IR, visible, and UV frequencies up to 1750 THz and 1625 THz, respectively. The Si_3N_4 substrate is a better choice for the IR and Visible frequencies only. From Fig. 4(b) it is observed that losses in these dielectrics are lower than the Ag metal when they show a negative permittivity behavior. As a result, these conducting oxides give a way to design a transparent optical antenna.



(a) (b)

Figure 4. Permittivity of substrate materials using Lorentz model. (a) Real part of Permittivity. (b) Imaginary part of Permittivity.

The variation of real and imaginary parts of the refractive index of dielectric substrates is as shown in Figs. 5(a) and (b), respectively. It is observed that the SiO_2 has a lower extinction coefficient, and it is suitable for the propagation of light among the other substrates. At 2875 THz, it shows a high value of refractive index, and after 3000 THz it shows low refractive index. For the ZnO, ITO, and Si_3N_4 substrates, this range is reduced to 1750 THz, 1650 THz, and 750 THz, respectively, and at these frequencies they show a negative permittivity behavior. Due to this fact, SiO_2 is more popularly used as a substrate material in Nano-antennas.



(a) (b)

Figure 5. Refractive index of dielectric substrates. (a) Real part of refractive index. (b) Imaginary part of refractive index.

4. RESULTS AND DISCUSSIONS

The performance analysis of the T-shaped Nano dipole using the eight plasmonic metals Ag, Au, Al, Cu, Cr, W, Ti, and Ni on the four dielectric materials SiO_2, ZnO, ITO, and Si_3N_4 is discussed in this section. The performance parameters considered for the discussion are reflection coefficient, radiation pattern, and directivity of the designed T-shaped Nano dipole antenna.

4.1. Impact of the Plasmonic Metals on Silicon Dioxide Based Nano Dipole Antenna

Fig. 6 shows reflection coefficient (S_{11}) of the designed T-shaped Nano dipole antenna on the Silicon dioxide substrate using the eight plasmonic metals. The Ag Nano structure resonates at 106 THz and 236 THz with magnitudes -15.72 dB and -23.4 dB, respectively. The Au Nano structure resonates at 89 THz with magnitude -13 dB; Al is at 286 THz with -24 dB; Cu is at 101 THz with -26.5 dB; and Cr is at 134 THz with -19.24 dB. All these metals show good S_{11} characteristics, and it is observed that the Cu, Al, and Ag Nano-antennas show the best characteristics on the Silicon dioxide substrate in the

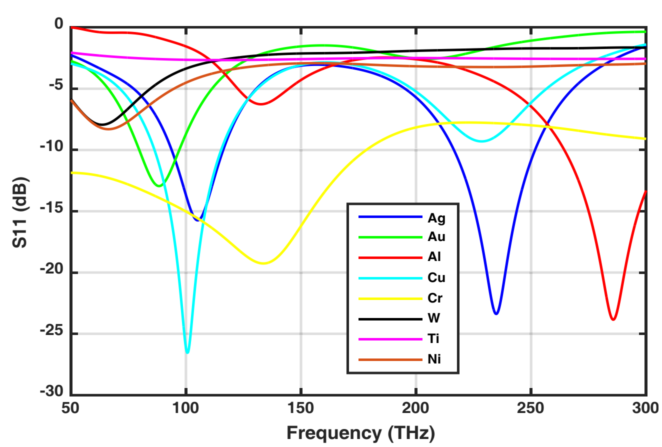
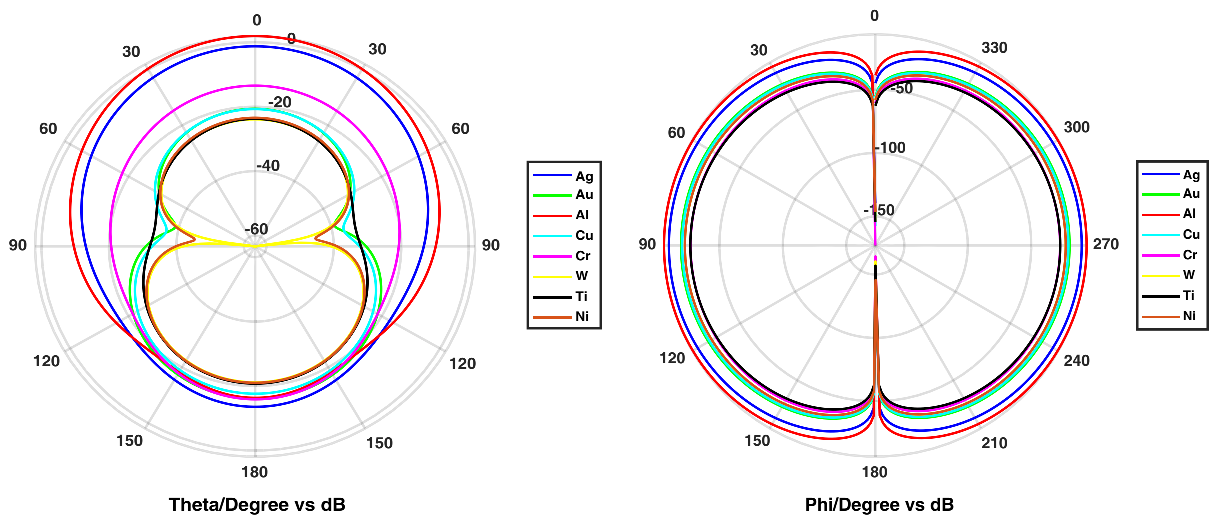


Figure 6. S_{11} parameters of Silicon Dioxide based Nano dipole antenna.

optical frequency region. The W, Ti and Ni Nano dipole antennas do not exhibit good S_{11} characteristics on the SiO_2 substrate, and hence they are not preferable for the optical wireless communication on this substrate.

Figs. 7(a) and (b) show the E and H radiation patterns of the designed T-shaped Nano dipole antenna on the SiO_2 substrate using the eight plasmonic metals. The combined plot is constructed to just compare the radiation patterns of the SiO_2 based Nano dipole antenna on the eight metals using auto scale. The eight-shaped E pattern has been changed because of the scale variation whereas magnitude in dB is the same as the original. The individual E patterns show main and back lobes properly. It is observed that the Ag and Al Nano-antennas show low back lobe radiation compared to other structures. The Half Power Beam Width (HPBW) and directivity of the eight radiation patterns of the metal Nano antenna are tabulated in Table 1. It is observed that the Ag Nano-antenna shows the highest directivity of 6.615 dBi on the SiO_2 substrate.



(a) (b)

Figure 7. Radiation pattern of Silicon Dioxide based Nano dipole antenna. (a) E plane. (b) H plane.

Table 1. HPBW and directivity of Silicon Dioxide based Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
Ag	82.8	94.1	6.615
Au	90.3	87.5	4.384
Al	82.1	111.4	6.338
Cu	90.3	88.0	3.891
Cr	94.2	103.4	5.145
W	90.7	89.0	3.194
Ti	89.5	87.0	4.802
Ni	91.3	88.9	3.191

4.2. Impact of the Plasmonic Metals on Zinc Oxide Based Nano Dipole Antenna

The reflection coefficient of the designed T-shaped Nano dipole antenna on the Zinc Oxide substrate using the eight plasmonic metals is depicted in Fig. 8. The Ag Nano structure resonates at 226 THz

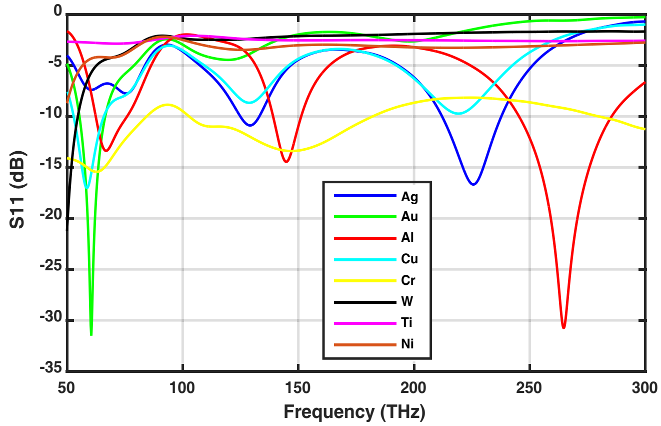


Figure 8. S_{11} parameters of Zinc Oxide based Nano dipole antenna.

with magnitude −16.64 dB. The Au Nano structure resonates at 61 THz with magnitude −31.4 dB; Al is at 265 THz with −30.63 dB; Cu is at 60 THz with −16.899 dB; Cr is at 63 THz with −15.414 dB; and W is at 50 THz with −21 dB. It is observed that the Au, Al and W Nano-antennas show the best S_{11} characteristics on the ZnO substrate. The Ti and Ni Nano dipole antennas do not show good S_{11} characteristics on the ZnO substrate.

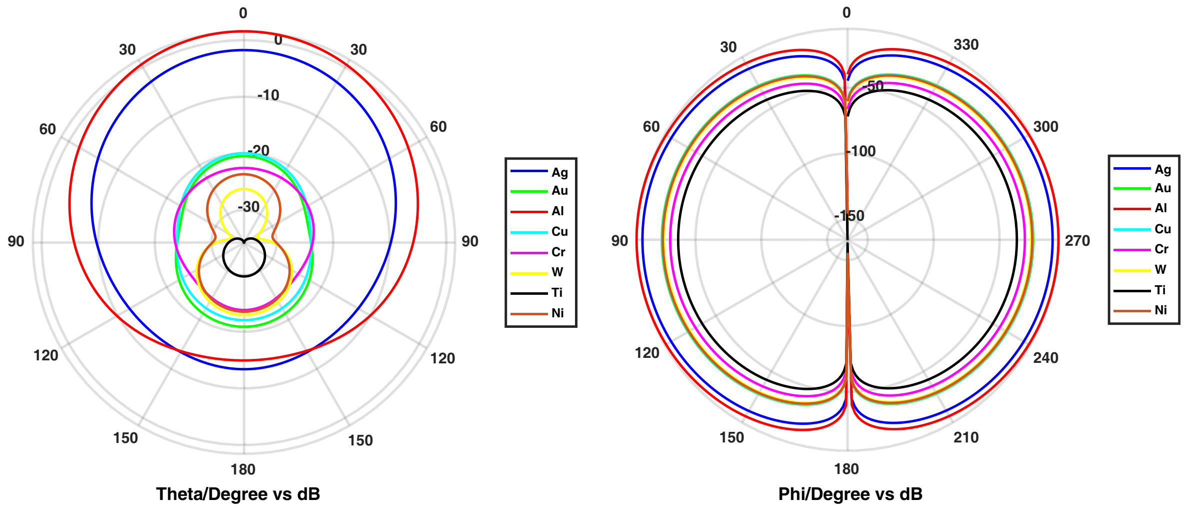
The E and H radiation patterns of the designed T-shaped Nano dipole antenna on the ZnO substrate using the eight plasmonic metals are as shown in Figs. 9(a) and (b). It is observed that the Ag, Cu, Cr, W, and Al Nano-antennas show low back lobe radiation as compared to the other structures. The HPBW and directivity of the eight radiation patterns of the metal Nano antenna are shown in Table 2. It is observed that the Ag Nano-antenna shows the highest directivity of 5.671 dBi on the ZnO substrate.

Table 2. HPBW and directivity of Zinc Oxide based Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	*H* Plane (Degree)	
Ag	98.6	92.1	5.671
Au	121.5	90.4	2.250
Al	106.5	93.7	5.318
Cu	124.1	90.5	2.931
Cr	178.5	88.2	2.24
W	118.1	89.5	3.361
Ti	170.4	91.2	3.685
Ni	120.5	89.8	2.031

4.3. Impact of the Plasmonic Metals on Indium Tin Oxide Based Nano Dipole Antenna

Fig. 10 shows the reflection coefficient of the designed T-shaped Nano dipole antenna on an ITO substrate using the eight plasmonic metals. The Ag Nano structure resonates at 69 THz with magnitude −35.922 dB. The Au Nano structure resonates at 68 THz with magnitude −14 dB; Al is at 88 THz with −20 dB; Cu is at 67 THz with −18.178 dB; Cr is at 77 THz with −31.147 dB; W is at 50 THz with −12 dB; and Ni is at 50 THz with −10 dB. All these metals show good S_{11} characteristics on the ITO substrate at low THz frequency. It is observed that the Ag, Cr, and Al Nano-antennas show better characteristics on the ITO substrate than the Ti and Ni Nano dipole antennas for the optical wireless communication.



(a) (b)

Figure 9. Radiation pattern of Zinc Oxide based Nano dipole antenna. (a) E plane. (b) H plane.

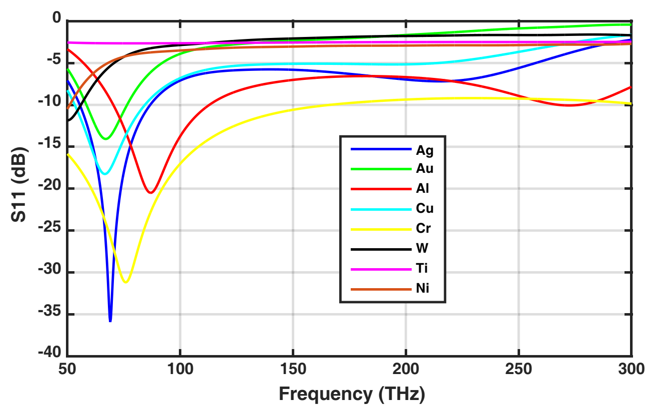
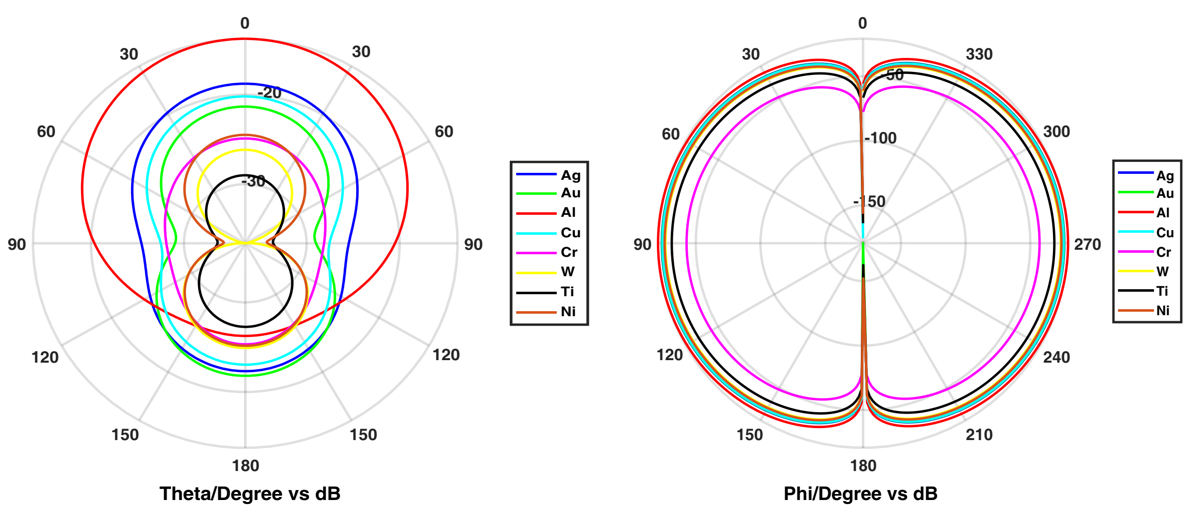


Figure 10. S_{11} parameters of Indium Tin Oxide based Nano dipole antenna.



(a) (b)

Figure 11. Radiation pattern of Indium Tin Oxide based Nano dipole antenna. (a) E plane. (b) H plane.

Figs. 11(a) and (b) show the E and H radiation patterns of the designed T-shaped Nano dipole antenna on the ITO substrate using the eight plasmonic metals. It is observed that the Ag, Cu and Cr Nano-antennas show low back lobe radiation compared to the other structures. The HPBW and directivity of the eight radiation patterns of the metal Nano antenna are given in Table 3. It is observed that the Al Nano-antenna shows the highest directivity of 5.066 dBi on the ITO substrate.

Table 3. HPBW and directivity of Indium Tin Oxide based Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
Ag	104.9	90.3	3.837
Au	92.3	89.5	2.637
Al	117.8	91.8	5.066
Cu	100.7	90.1	3.565
Cr	163.4	91.5	3.315
W	100.0	89.6	2.674
Ti	103.8	90.1	3.196
Ni	91.4	89.8	2.377

4.4. Impact of the Plasmonic Metals on Silicon Nitride Based Nano Dipole Antenna

The reflection coefficient of the designed T-shaped Nano dipole antenna on a Si_3N_4 substrate using the eight plasmonic metals is shown in Fig. 12. The Ag Nano structure resonates at 209.5 THz with magnitude −25.119 dB. The Au Nano structure resonates at 82 THz with magnitude −18.27 dB; Al is at 254 THz with −27.184 dB; Cu is at 90 THz with −24 dB; Cr is at 118 THz with −39 dB; W is at 61 THz with magnitude −10 dB; Ni is at 59 THz with magnitude −11.373 dB. It is observed that the Cu, Cr, Al, and Ag Nano-antennas show the best characteristics on the Si_3N_4 substrate. The Ti, W, and Ni Nano dipole antennas do not show good S_{11} characteristics on the Si_3N_4 substrate.

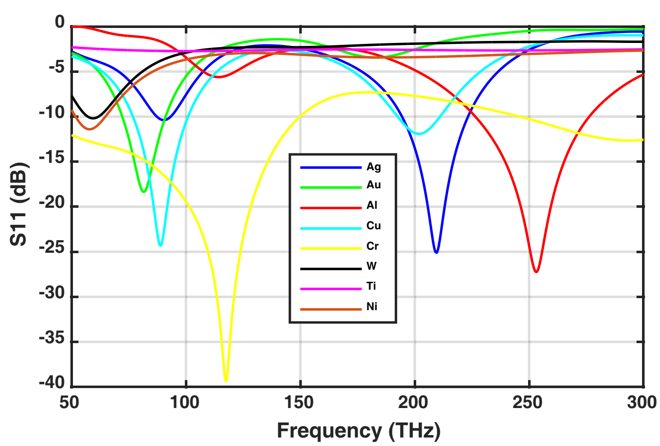
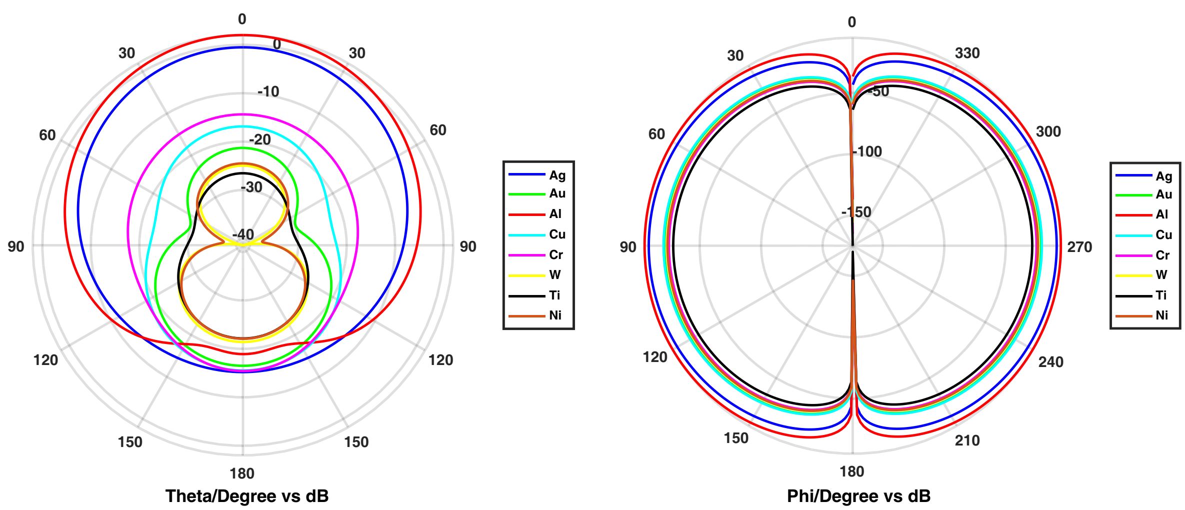


Figure 12. S_{11} parameters of Silicon Nitride based Nano dipole antenna.

The E and H radiation patterns of the designed T-shaped Nano dipole antenna on the Si_3N_4 substrate using the eight plasmonic metals are given in Figs. 13(a) and (b), respectively. It is observed that the Ag, Al and Cr Nano-antennas show low back lobe radiation compared to the other metals. Table 4 shows the HPBW and directivity of the eight radiation patterns of the metal Nano antenna. It is observed that the Ag Nano-antenna has the highest directivity of 5.709 dBi on the Si_3N_4 substrate.

Table 4. HPBW and directivity of Silicon Nitride based Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
Ag	103.6	92.5	5.709
Au	102.8	88.2	4.306
Al	105.2	118.6	5.286
Cu	112.7	90.0	3.431
Cr	162.1	90.0	3.461
W	98.3	90.0	3.449
Ti	105.4	88.7	4.519
Ni	99.1	89.2	3.047



(a) (b)

Figure 13. Radiation pattern of Silicon Nitride based Nano dipole antenna. (a) E plane. (b) H plane.

4.5. Impact of the Substrates on Silver Nano Dipole Antenna

Fig. 14 shows the reflection coefficient of the designed T-shaped Ag Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. The Ag Nanostructure resonates at 106 THz and 236 THz with magnitudes -15.72 dB and -23.4 dB, respectively on the SiO_2 substrate, at 226 THz with magnitude -16.64 dB on the ZnO substrate, at 69 THz with magnitude -35.922 dB on the ITO substrate, and at 209.5 THz with magnitude -25.119 dB on the Si_3N_4 substrate. It is observed that the Ag Nano dipole antenna shows very good characteristics on the ITO substrate at a low THz frequency. It shows two resonating frequencies on the SiO_2 substrate with good S_{11} characteristics.

The E and H radiation patterns of the designed T-shaped Ag Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates are given in Figs. 15(a) and (b), respectively. The HPBW and directivity of the four radiation patterns of the Ag Nano dipole antenna are tabulated in Table 5. It is observed that the Ag Nano-antenna has the highest directivity of 6.615 dBi on the SiO_2 substrate.

4.6. Impact of the Substrates on Gold Nano Dipole Antenna

The reflection coefficient of the designed T-shaped Au Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates is depicted in Fig. 16. The Au Nanostructure resonates at 89 THz with magnitude

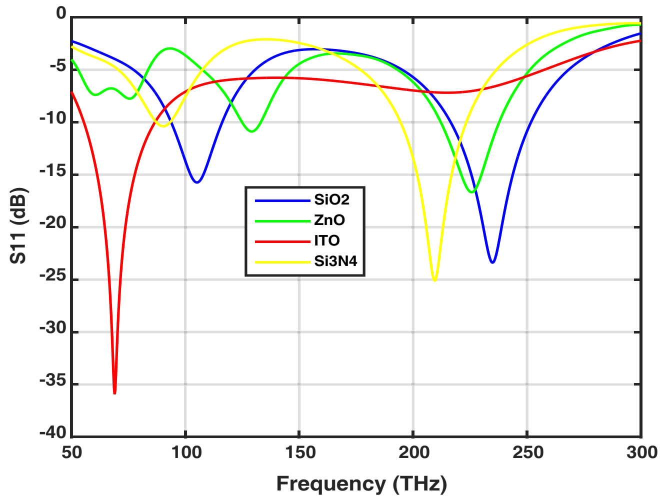
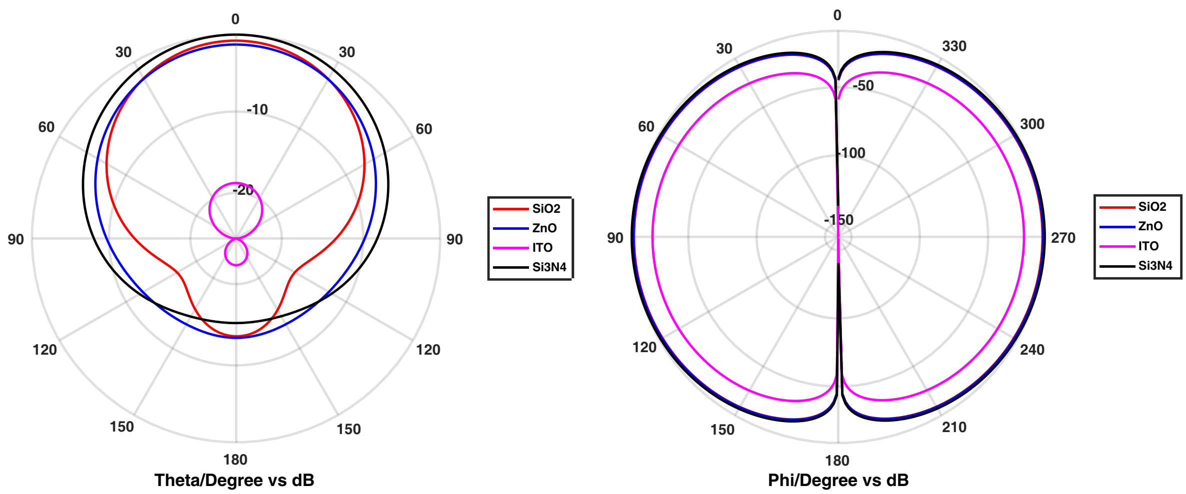


Figure 14. S_{11} parameters of Silver Nano dipole antenna.



(a) (b)

Figure 15. Radiation pattern of Silver Nano dipole antenna. (a) E plane. (b) H plane.

Table 5. HPBW and directivity of Silver Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
SiO_2	82.8	94.1	6.615
ZnO	98.6	92.1	5.671
ITO	104.9	90.3	3.831
Si_3N_4	103.6	92.5	5.709

−13 dB on the SiO_2 substrate, at 61 THz with magnitude −31.4 dB on the ZnO substrate, at 68 THz with magnitude −14 dB on the ITO substrate, and at 82 THz with magnitude −18.27 dB on the Si_3N_4 substrate. It is observed that the Au Nano dipole antenna radiates at a low THz frequency on all the substrates. It shows the best S_{11} characteristics on the ZnO substrate.

Figs. 17(a) and (b) show the E and H radiation patterns of the designed T-shaped Au Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. The HPBW and directivity of the four radiation patterns of the Au Nano dipole antenna are given in Table 6. It is observed that Au Nano-antenna has the highest directivity of 4.384 dBi on the SiO_2 substrate.

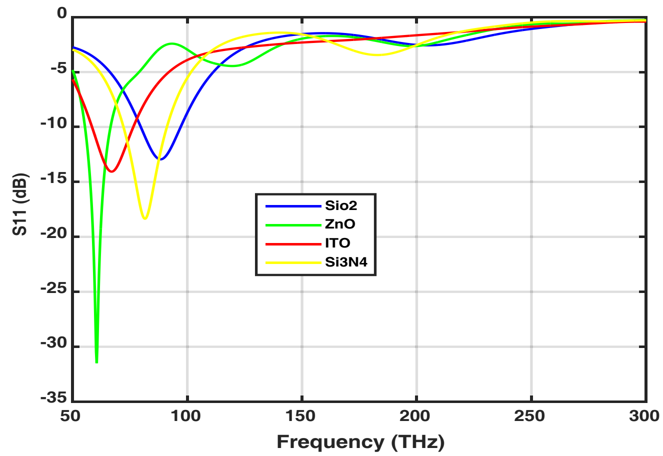


Figure 16. S_{11} parameters of Gold Nano dipole antenna.

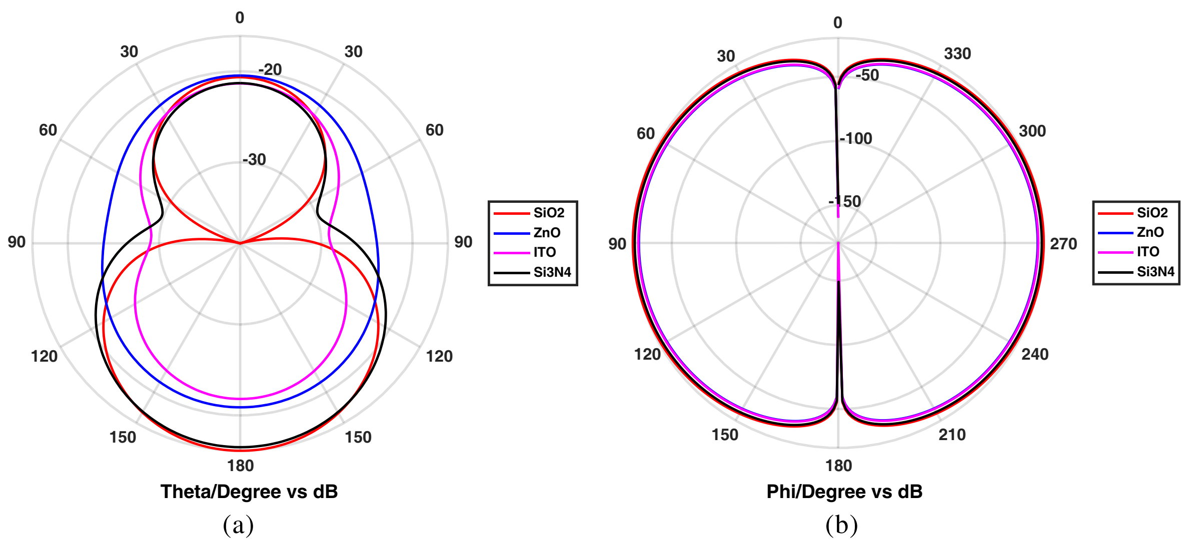


Figure 17. Radiation pattern of Gold Nano dipole antenna. (a) E plane. (b) H plane.

Table 6. HPBW and directivity of Gold Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
SiO_2	90.3	87.5	4.384
ZnO	121.5	90.4	2.250
ITO	92.3	89.5	2.637
Si_3N_4	102.8	88.2	4.306

4.7. Impact of the Substrates on Aluminium Nano Dipole Antenna

The reflection coefficient of the designed T-shaped Al Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates is shown in Fig. 18. The Al Nanostructure resonates at 286 THz with −24 dB on the SiO_2 substrate, at 265 THz with −30.63 dB on the ZnO substrate, at 88 THz with −20 dB on the ITO substrate, and at 254 THz with −27.184 dB on the Si_3N_4 substrate. It is observed that the Al Nano dipole antenna radiates at multiple frequencies with very good S_{11} characteristics on the ZnO substrate, and it resonates at a low THz frequency on the ITO substrate as compared to the other substrates.

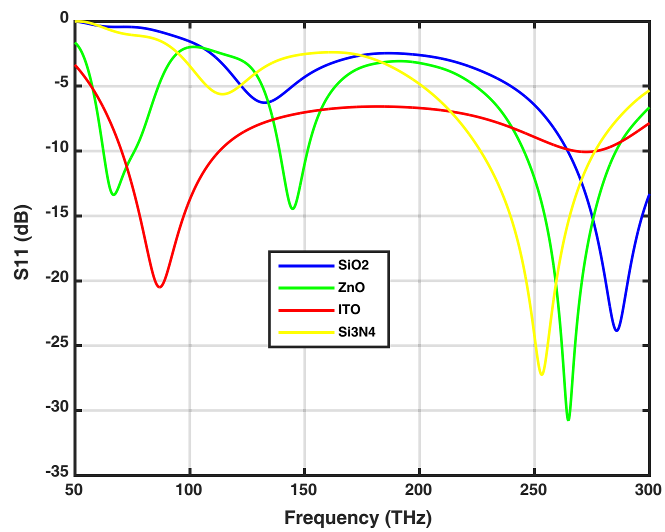


Figure 18. S_{11} parameters of Aluminium Nano dipole antenna.

Figs. 19(a) and (b) show the E and H radiation patterns of the designed T-shaped Al Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. The HPBW and directivity of the four radiation patterns of the Al Nano dipole antenna are tabulated in Table 7. It is observed that the Al Nano-antenna has the highest directivity of 6.338 dBi on the SiO_2 substrate.

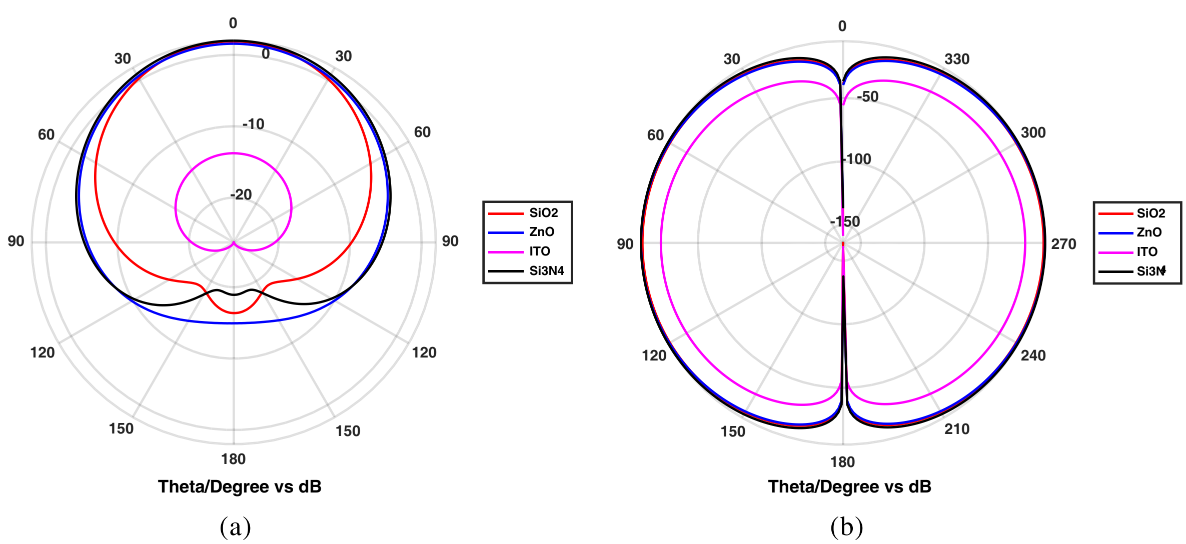


Figure 19. Radiation pattern of Aluminium Nano dipole antenna. (a) E plane. (b) H plane.

Table 7. HPBW and directivity of Aluminium Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	*H* Plane (Degree)	
SiO_2	82.1	111.4	6.338
ZnO	106.5	93.7	5.318
ITO	117.8	91.8	5.066
Si_3N_4	105.2	118.6	5.286

4.8. Impact of the Substrates on Copper Nano Dipole Antenna

Fig. 20 shows the S_{11} characteristics of the designed T-shaped Cu Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. The Cu Nanostructure resonates at 101 THz with -26.5 dB on the SiO_2 substrate, at 60 THz with -16.899 dB on the ZnO substrate, at 67 THz with -18.178 dB on the ITO substrate, and at 90 THz with -24 dB on the Si_3N_4 substrate. It is observed that Cu Nano dipole antenna radiates at low THz frequency on all the four substrates. Comparatively, it shows a good characteristics on the Silicon based substrates.

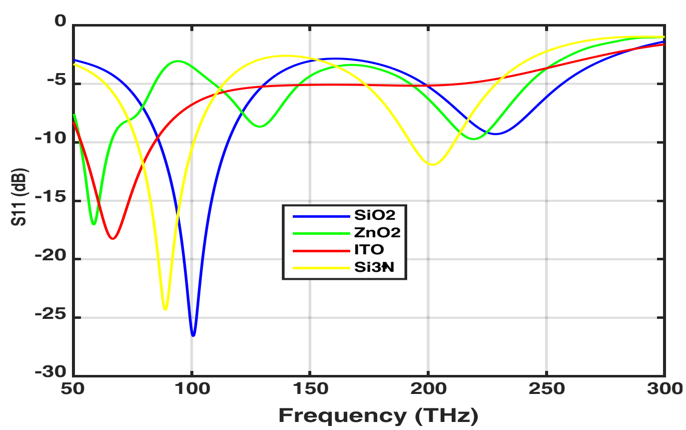


Figure 20. S_{11} parameters of Copper Nano dipole antenna.

Figs. 21(a) and (b) show the E and H radiation patterns of the designed T-shaped Cu Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. The HPBW and directivity of the four radiation patterns of the Cu Nano dipole antenna are given in Table 8. It is observed that the Cu Nano-antenna has the highest directivity of 3.891 dBi on the SiO_2 substrate.

Table 8. HPBW and directivity of Copper Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	*H* Plane (Degree)	
SiO_2	90.3	88.0	3.891
ZnO	124.1	90.5	2.931
ITO	100.7	90.1	3.565
Si_3N_4	112.7	90.0	3.431

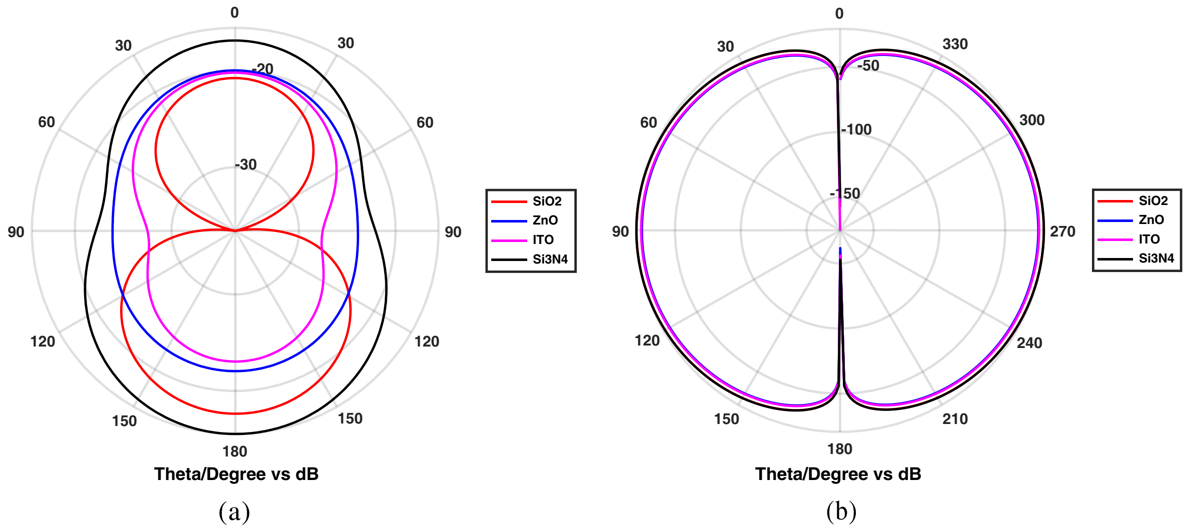


Figure 21. Radiation pattern of Copper Nano dipole antenna. (a) E plane. (b) H plane.

4.9. Impact of the Substrates on Chromium Nano Dipole Antenna

The S_{11} characteristics of the designed T-shaped Cr Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates are shown in Fig. 22. The Cr Nanostructure resonates at 134 THz with −19.24 dB on the SiO_2 substrate, at 63 THz with −15.414 dB on the ZnO substrate, at 77 THz with −31.147 dB on the ITO substrate, and at 118 THz with −39 dB on the Si_3N_4 substrate. It shows good characteristics on the Si_3N_4 substrate.

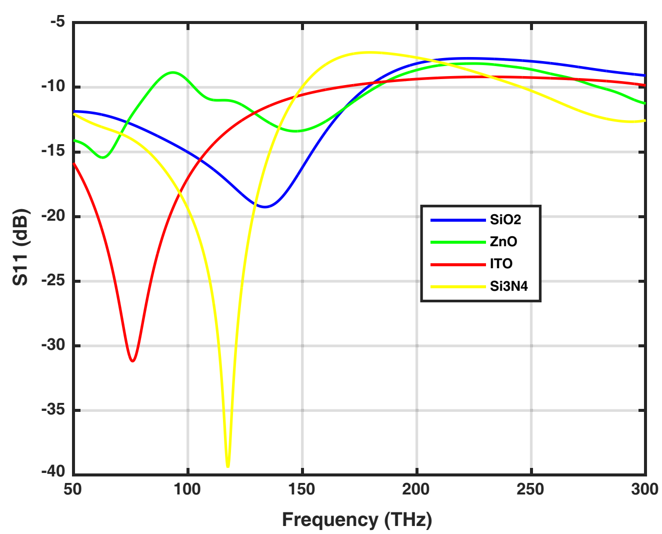


Figure 22. S_{11} parameters of Chromium Nano dipole antenna.

Figs. 23(a) and (b) show the E and H radiation patterns of the designed T-shaped Cr Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. The HPBW and directivity of the four radiation patterns of the Cr Nano dipole antenna are tabulated in Table 9. It is observed that the Cr Nano-antenna has the highest directivity of 5.145 dBi on SiO_2 substrate.

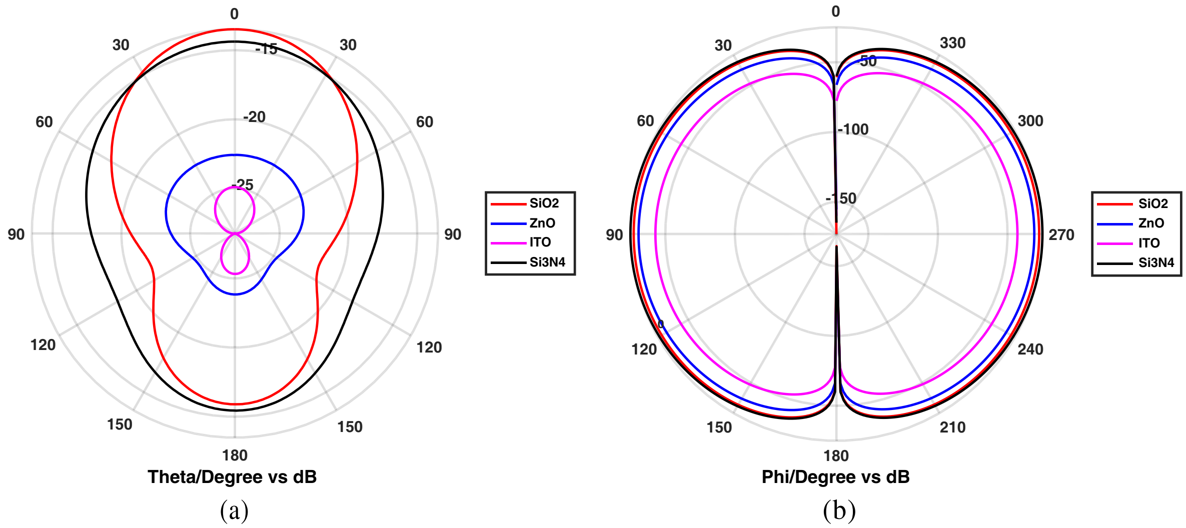


Figure 23. Radiation pattern of Chromium Nano dipole antenna. (a) E plane. (b) H plane.

Table 9. HPBW and directivity of Chromium Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
SiO_2	94.2	103.4	5.145
ZnO	178.5	88.2	2.24
ITO	163.4	91.5	3.315
Si_3N_4	162.1	90.0	3.461

4.10. Impact of the Substrates on Tungsten Nano Dipole Antenna

The S_{11} characteristics of the designed T-shaped W Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates are given in Fig. 24. The W Nanostructure resonates at 50 THz with -21 dB on the ZnO substrate, at 50 THz with -12 dB on the ITO substrate, and at 61 THz with magnitude -10 dB on the Si_3N_4 substrate. It is observed that the W Nano dipole shows poor S_{11} characteristics on the SiO_2 substrate and resonates at a low THz frequency on the other substrates.

The E and H radiation patterns of the designed T-shaped W Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates are shown in Figs. 25(a) and (b). The HPBW and directivity of the four radiation patterns of the W Nano dipole antenna are given in Table 10. It is observed that the W Nano-antenna has the highest directivity of 3.449 dBi on the Si_3N_4 substrate.

Table 10. HPBW and directivity of Tungsten Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
SiO_2	90.7	89.0	3.194
ZnO	118.1	89.5	3.361
ITO	100.0	89.6	2.674
Si_3N_4	98.3	90.0	3.449

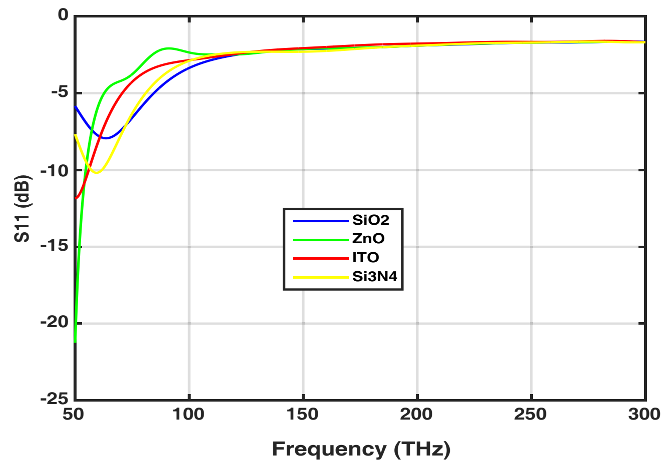


Figure 24. S_{11} parameters of Tungsten Nano dipole antenna.

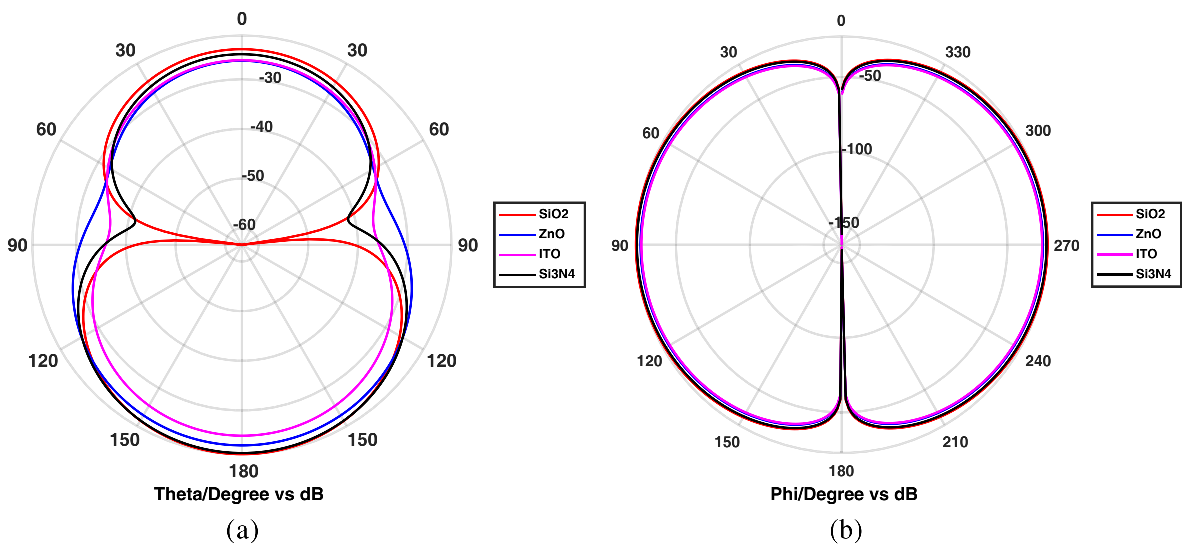


Figure 25. Radiation pattern of Tungsten Nano dipole antenna. (a) E plane. (b) H plane.

4.11. Impact of Substrates on Titanium Nano Dipole Antenna

Fig. 26 shows the S_{11} characteristics of the designed T-shaped Ti Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. The designed Nano dipole antenna using Ti shows poor S_{11} characteristics on all the four substrates, hence it is not preferable on these substrates for optical communication.

Figs. 27(a) and (b) show the E and H radiation patterns of the designed T-shaped Ti Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates. Table 11 gives the HPBW and directivity of the four radiation patterns of the Ti Nano dipole antenna. It is observed that the Ti Nano-antenna shows the highest directivity of 4.802 dBi on SiO_2 substrate.

4.12. Impact of the Substrates on Nickel Nano Dipole Antenna

The S_{11} characteristics of the designed T-shaped Ni Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates are shown in Fig. 28. The Ni Nanostructure resonates at 50 THz with -10 dB on the ITO substrate and at 59 THz with magnitude -11.373 dB on the Si_3N_4 substrate. It is observed that the Ni

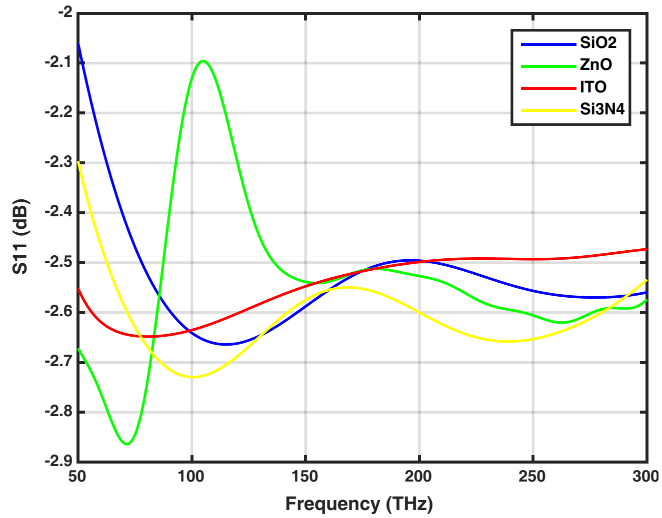


Figure 26. S_{11} parameters of Titanium Nano dipole antenna.

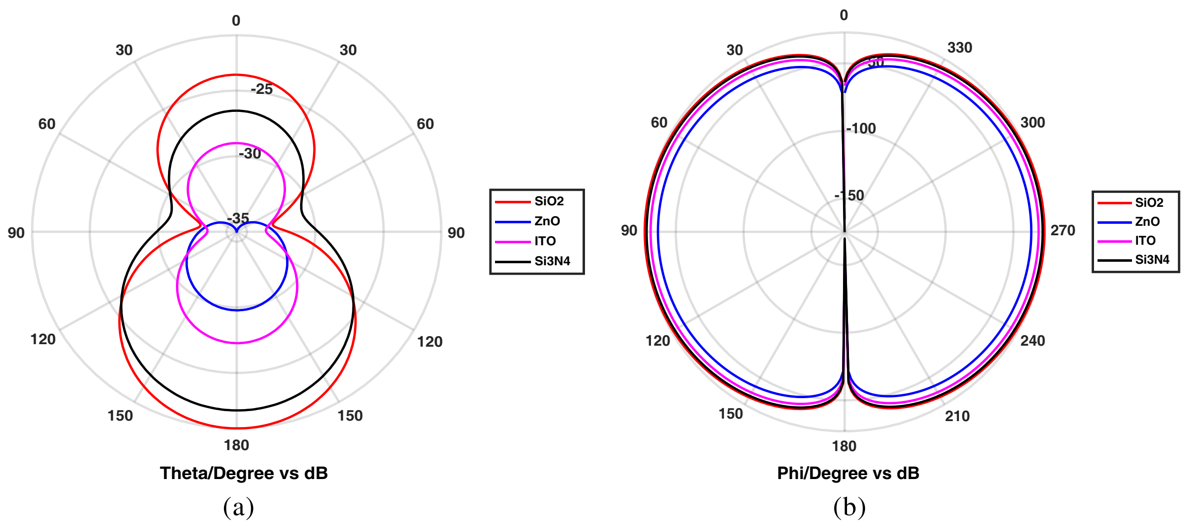


Figure 27. Radiation pattern of Titanium Nano dipole antenna. (a) E plane. (b) H plane.

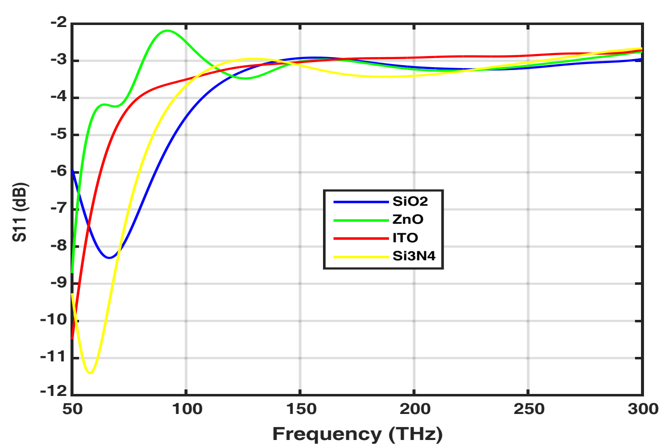


Figure 28. S_{11} parameters of Nickel Nano dipole antenna.

Table 11. HPBW and directivity of Tungsten Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
SiO_2	89.5	87.0	4.802
ZnO	170.4	91.2	3.685
ITO	103.8	90.1	3.196
Si_3N_4	105.4	88.7	4.519

Nano dipole shows poor S_{11} characteristics on the SiO_2 and ZnO substrates, and it resonates at a low THz frequency on the other substrates.

The E and H radiation patterns of the designed T-shaped Ni Nano dipole antenna on SiO_2, ZnO, ITO, and Si_3N_4 substrates are given in Figs. 29(a) and (b). The HPBW and directivity of the four radiation patterns are tabulated in Table 12. It is observed that the Ni Nano-antenna shows the highest directivity of 3.191 dBi on the SiO_2 substrate.

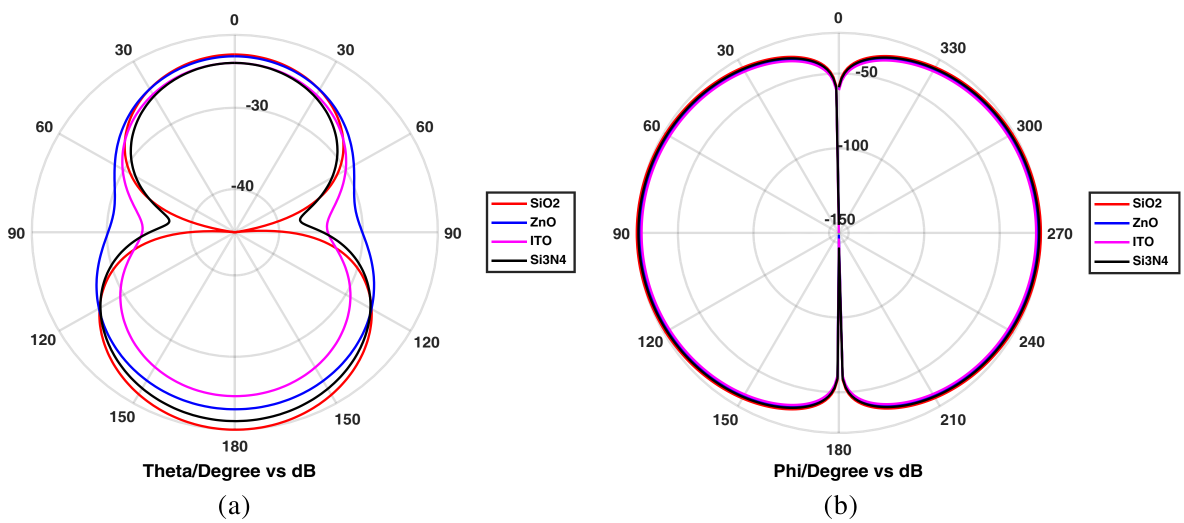


Figure 29. Radiation pattern of Nickel Nano dipole antenna. (a) E plane. (b) H plane.

Table 12. HPBW and directivity of Nickel Nano-antenna.

	HPBW		Directivity (dBi)
	E Plane (Degree)	H Plane (Degree)	
SiO_2	91.3	88.9	3.191
ZnO	120.5	89.8	2.031
ITO	99.1	89.2	3.047
Si_3N_4	91.4	89.8	2.377

The directivity of the Nano antenna depends on the metal-substrate combination. According to Snell's law, the optical wave propagation in optical metal and substrate of Nano antenna is related to the refractive index of metal-substrate combination, and it can be observed from Fig. 3(a) and Fig. 5(a). Since Al metal has a high refractive index compared to the other metals used, it gives a good directivity with all the substrate combinations. The directivity also depends on the losses occurring in the metal and substrate. Ag metal has moderate losses and refractive index, hence it shows a good directivity on all the substrates.

It is observed that for the optical communication, the best S_{11} characteristics combinations are the Cr-Si_3N_4 at 118 THz with magnitude −39 dB, Ag-ITO at 69 THz with magnitude −35.922 dB, Au-ZnO at 61 THz with magnitude −31.4 dB, Cr-ITO at 77 THz with magnitude −31.147 dB, Al-ZnO at 265 THz with magnitude −30.63 dB, Al-Si_3N_4 at 254 THz with magnitude −27.184 dB, Cu-SiO_2 at 101 THz with magnitude −26.5 dB, Ag-Si_3N_4 at 209.5 THz with magnitude −25.119 dB, Cu-Si_3N_4 at 90 THz with magnitude −24 dB, Al-SiO_2 at 286 THz with magnitude −24 dB, Ag-SiO_2 at 236 THz with magnitude −23.4 dB, W-ZnO at 50 THz with magnitude −21 dB, and Al-ITO at 88 THz with magnitude −20 dB.

5. CONCLUSION

The T-shaped Nano dipole antenna is designed and investigated on SiO_2, ZnO, ITO, and Si_3N_4 substrates using Ag, Au, Al, Cu, Cr, W, Ti, and Ni plasmonic metals for THz optical wireless communication. It is observed that the Ag Nano dipole antenna has directivities of 6.615 dBi, 5.671 dBi, and 5.709 dBi on the SiO_2, ZnO, and Si_3N_4 substrates, respectively which are higher than the other used metals. On the ITO substrate the Al Nano-antenna shows the highest directivity of 5.066 dBi. It is observed from Drude model that Al metal is applicable to high THz application. Ag and Al metals are suitable for visible region with moderate losses among the other used metals. It is noticed from Lorentz model that the SiO_2 substrate is applicable to a wide range of THz frequencies. It is further observed that metal-substrate combination affects the characteristics of Nano-antenna significantly. In directivity perspective Ag-SiO_2, Ag-ZnO, Ag-Si_3N_4, and Al-ITO are the best metal-substrate combinations that can be used for the optical wireless applications.

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