Bulletin of Electrical Engineering and Informatics
Vol. 11, No. 5, October 2022, pp. 2672~2678
ISSN: 2302-9285, DOI: 10.11591/eei.v11i5.4129

Wideband improvement for hybrid plasmonic fractal patch nanoantenna

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Article Info

Article history:

Received May 29, 2022
Revised Jun 28, 2022
Accepted Jul 19, 2022

Keywords:

Chip optical communication
Plasmonic fractal patch nano-antenna
Plasmonic patch nano-antenna
THz plasmonic nano-antenna design
Wideband plasmonic nano-antenna

ABSTRACT

A wideband improvement for hybrid plasmonic fractal patch nanoantenna is presented for use in intra/inter chip optical interconnects. The suggested fractal patch antenna covering a part of U-band (1625-1675 nm), L-band (1565-1625nm), C-band (1530-¬1565nm), S-band (1460-1530nm), E-band (1360-1460nm) and most of O-band (1260-1360nm) optical communication bands. The proposed antenna has a promising future use in inter and intra chip optical communications to eliminate electrical interconnection limitations such as interconnect density, power consumption and also increasing data rate. The performance of this antenna has been evaluated using full wave simulation computer simulation technology (CST) Microwave software. The impedance bandwidth is largely enhanced by applying rectangular fractal cuts to the both sides of patch. The proposed antenna achieves a wider bandwidth from 168 THz to 228 THz (B.W.=60 THz), which is about 8 times greater the bandwidth of reference antenna with a good gain and more than 95% radiation efficiency throughout the operational bandwidth.

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1. INTRODUCTION

Electrical interconnects face a tremendous problem (heat dissipation, signal latency, cross talk and bandwidth). To break through the limitations of electrical interconnects, optical interconnects have been proposed as a replacement of global electrical interconnect because of their almost distance-independent power consumption and low latency and high bandwidth. However, size of dielectric waveguides used in silicon photonics is fundamentally limited by diffraction optics, posing a limit on the maximum achievable density which leads to mismatch between optics and electronics in such interconnect technology.

Plasmonic has been regarded as an alternative solution to electrical and dielectric waveguide. Plasmonic circuits have enabled light-matter interactions at a sub-wavelength size comparable to electronics and transfer information at optical speed, however at the cost of metal dissipation loss. The main challenge that faces plasmonic waveguides is to achieve high confinement with a long propagation distance [1]–[3].

Optical wireless links using plasmonic nanoantenna would exhibit much less absorption losses [4]. Despite many nanoantennas have been proposed to operate in optical frequencies, most of these antennas have an extremely poor far-field radiation and used for spectroscopy, microscopy, and energy harvesting. Therefore, they cannot be utilized like conventional antennas in transmission and reception of optical signals wirelessly. Optical antenna has been suggested to play a vital role in on-chip and intra-chip optical interconnect as an alternative solution to plasmonic waveguide. In this context, nanoantenna could be considered as an effective solution to the limitations of electrical interconnects (heat dissipation, signal latency, cross talk, bandwidth and bottleneck) and dissipation loss in the plasmonic waveguides the next generation integrated circuits (ICs) [5].

Most of the studies that have been reported in the nanoantenna literature are either have low radiation efficiency or limited bandwidth because of their dipolar nature, therefore only suitable for narrow band applications [6]. In an effort to surpass the limitations of narrow band operation, many types of conventional broadband and multiband antennas have been translated nanoantenna to take advantage of their broadband/multiband behavior for several applications such as spiral, bow tie, log-periodic, trapezoidal, fractal Sierpinski, Yagi-Uda, and dual-Vivaldi nanoantenna [6]–[13].

A realistic waveguide-fed nano patch antenna based on hybrid metal-insulator-metal (HMIM) plasmonic waveguide is proposed and developed [14]. Their antenna exhibits a bandwidth of 49.5 THz (151.5 THz–201 THz). While modified wide band E-shaped nano-antenna is designed in [15]. This model is introduced with higher gain at frequency range from 190 THz to 200 THz (a bandwidth 10 THz).

Fractal antenna shows interesting features, some of fractal geometries have been particularly useful to miniaturize the antenna, while other designs aim at incorporating multiband/wideband characteristics [16]. The idea of using fractal geometries in RF/microwave antennas had been discussed in detail and investigated both numerically and practically in many publications. In contrast to fractal antenna in the microwave regime, optical fractal antenna only discussed in a few papers to benefit from fractal geometry features [8]. In additional to the multiband or wideband characteristics and consistent performance over the operating frequency band, the use of fractal concept in optical antenna gives an additional miniaturization, and a potential importance for reducing mutual coupling in the potential future high density plasmonic circuits for instance nanoantenna solar cell application [17], [18], since the effective nanoantenna solar panels contain billions of nanoantennas [19].

2. MICRO-STRIP NANOANTENNA

Micro-strip nanoantenna was first introduced in [20] which is based on the hybrid plasmonic waveguide. It's providing a frequency bandwidth about 15.6, where $S11<-10$ dB and a gain of 5.6 dB. Its bandwidth corresponds to the wavelength range of 1463 nm-1580 nm, which covers most of the standard optical communication bands of S and C.

The hybrid plasmonic waveguide is a combining of plasmonic and dielectric waveguides. In hybrid plasmonic structure the transverse magnetic (*TM*) surface plasmon wave is supported by metal/dielectric interface couples with the *TM* mode dielectric waveguide and results a hybrid mode which is also a *TM* mode [21], [22]. Figure 1 shown the hybrid mode, power is mainly confined in the 50 nm low index material (SiO_2 in the paper) [20].

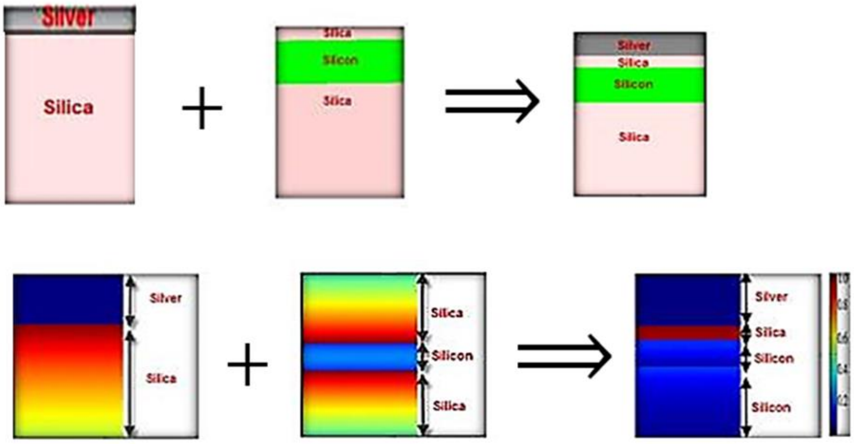


Figure 1. Hybrid waveguide formation and the resulting hybrid mode from coupling of dielectric and SP mode with silica height $h_{SiO_2} = 50$ nm at wavelength $= 1550$ nm

The surface plasmon theory [23] showed the validity of the transmission line model to predict the impedance of the patch antenna. Transmission line model represents the micro-strip patch antenna by two slots of width (*W*) and height *h* separated by a transmission line of length (*L*). The hybrid *TM* mode of the hybrid structure approximated as a transmission electron microscopy (*TEM*), note that due to surface plasmon resonance the ratio of x-component $\boldsymbol{E_x}$ (the direction along the waveguide) to the perpendicular z-component $\boldsymbol{E_z}$ is given by the boundary condition relation.

$$\frac{E_x}{E_z} = \frac{K_z}{K_x} = \sqrt{\frac{\epsilon_d}{\epsilon_m}} \tag{1}$$

where K_X and K_Z are the propagation constants in the x and z directions, while ϵ_m and ϵ_d are permittivity of metal (which can be gold or silver) and dielectric respectively. At the optical frequencies the ratio of ϵ_d to ϵ_m is very small, therefore the value of $\boldsymbol{E_x}$ is negligible compared with the dominant $\boldsymbol{E_z}$ value. Consequently, the *TM* mode can be approximated to as a *TEM* mode [20].

Figure 2 shows the optical patch nanoantenna, the reference antenna, which is based on hybrid plasmonic structure. The antenna consists of three materials stacked on top of each other (metal-low refractive index material-high refractive index material) placed on the buffer layer with low refractive index. In this paper the materials are silver (Ag), silicon dioxide (SiO_2) and silicon (Si) substrate and SiO_2 as a buffer layer. The patch is center-fed by a hybrid plasmonic waveguide which provides a better compromise between loss and confinement better than other plasmonic waveguide types [21].

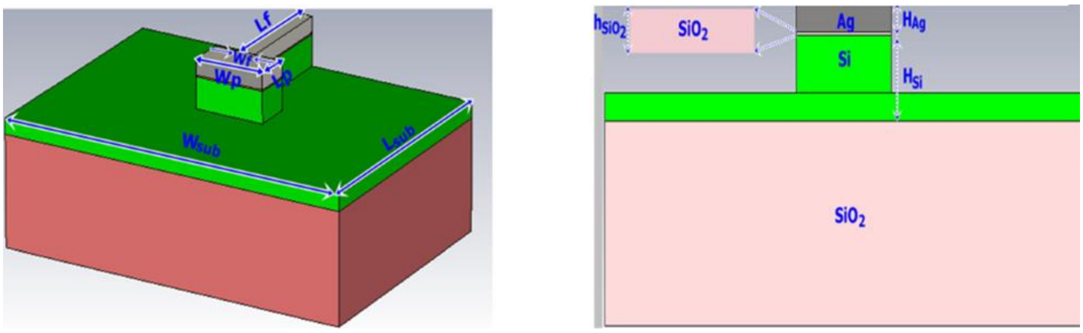


Figure 2. Micro-strip nanoantenna (Reference antenna)

The nanoantenna should be matched to the waveguide to get a good -10 dB S_{11} performance. The impedance of patch antenna at the resonance condition ($\boldsymbol{L} = \frac{\lambda_g}{2}$ for the dominant ***TM₀₁₀*** mode) is calculated as:

$$Z_{antenna} = \frac{1}{Y_{in}} = \frac{1}{2G}, G = \frac{W_p}{120\lambda_o}\left[1 - \frac{1}{24}\left(\frac{2\pi h}{\lambda_o}\right)^2\right] \tag{2}$$

where G is the conductance, while W_p the width of patch antenna and h is the height of SiO_2 layer.

$$Z_{waveguide} = \frac{Z_o}{n_{eff}} = \frac{377}{n_{eff}} \tag{3}$$

where Z_o is the characteristic impedance of air and n_{eff} is the effective refractive index of the structure.

The effective refractive index is non-linearly dependent on structure dimensions. The dimensions $(W, h_{SiO_2}, h_{Ag}, h_{Si})$ have a significant effect on three main parameters refractive index n_{eff}, propagation distance and power confinement, for instance decreasing h_{SiO_2} lead to decrease in n_{eff}, increase in propagation distance and power confinement values [21]. For the comparison purpose, the dimensions for the reference antenna in Figure 2 have been set equal to that considered in [20]. Metals, in particular, gold, are commonly used to fabricate antennas in the THz frequency range. At THz frequencies, the lower conductivity of metal, compared to its DC conductivity [24], [25].

3. THE PROPOSED MODEL

The suggested design is a hybrid of the suggested design in [26] appropriate rectangular fractal cut as perturbations on the sides edge of fractal geometries: rectangular fractal slit as reported in [26] is made by slitting the metal at the top edge of the radiating patch with dimensions ($Ws_n \times Ls_n$) where n is the number of iterations. Figure 3(a) to (b) illustrates the radiating patch with rectangular fractal slit. CST 2020 (Computer Simulation Technology) [27] software utilized to simulate the proposed antenna.

$$Ws_n = (^3/_4)^n \, Wp \tag{4}$$

$$Ls_n = (^1/_4)^n \, Lp \tag{5}$$

(a) (b) (c)

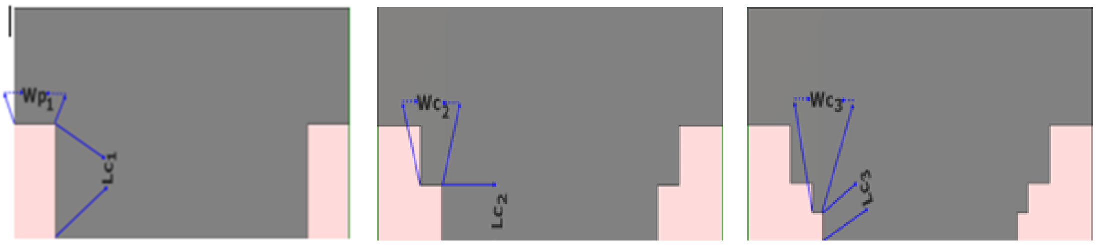
Figure 3. Micro-strip nano fractal antenna with top side fractal [26] for (a) 1st iteration, (b) 2nd iteration, and (c) 3rd iteration

The second stage is accomplished by applying the same fractal concept that is indicated above to the two sides' edge of the patch as illustrated in (6) and (7). The first, second, and third iteration of the two sides' edge of the patch show in Figures 4(a) to (c) respectively.

$$Wc_n = (^1/_2)^n \, Wp/4 \tag{6}$$

$$Lc_n = (^1/_2)^n \, Lp \tag{7}$$

The final design of the modified micro-strip nano fractal patch antenna, shown in Figure 5 is a combination of the two nano fractal antenna designs above, as shown in Figures 3 and 4. Figure 5 shown the structure of the proposed geometry for Figures 5 (a) antenna with top edge fractal, 5(b) antenna with two sides' edge fractals, while 5(c) included the final proposed model.



(a) (b) (c)

Figure 4. Micro-strip nano fractal patch antenna with two sides' edge fractal for (a) 1st iteration, (b) 2nd iteration, and (c) 3rd iteration

(a) (b) (c)

Figure 5. Structure of the proposed geometry for (a) antenna with top edge fractal [26], (b) antenna with two sides' edge fractals, and (c) the final proposed model

4. RESULTS AND DISCUSSION

The finite integration method (FIT) is used for simulation this antenna with computer simulation technology (CST) microwave studio software [27]. The proposed antenna has been simulated and compared with the reference antenna and the same antenna geometry without fractal edge sides. Figure 6 shows a comparison of S_{11} reflection coefficient for the three antennas models. As shown in Figure 6, that the proposed model exhibits a good enhancement over the two other models in terms of bandwidth ($S_{11} \leq$ -10dB). The level of impedance matching is improved and also the dip at the fundamental resonance frequency has been greatly enhanced. A good gain achieved between 4.5 to 6 dB versus frequency range in the case of modified antenna model as shown in Figure 7.

The radiation pattern of the antenna has been simulated at the selected frequencies 180, 190, 200, 210 and 220 as shown in Figure 8(a) to (f) (see in appendix). A good consistent radiation pattern has been obtained over the bandwidth 60 THz (168 THz-228 THz). The radiation pattern is bi-directional broadside due to absence of ground plane. The antenna has a slightly shifted main beam about 15-20 degrees from the perpendicular direction to the plane of antenna (z-axis). A comparison made between the simulation results of our proposed model and published results of [14], [15], [20], and [26], as shown in Table 1. The antenna proposed in this work increased the bandwidth by 10.5 THz compared to the antenna published in [14].

Table 1. Comparison between bandwidth (BW) of proposed antenna with the published antennas

Refs.	[15]	[20]	[26]	[14]	This our work
B.W. (THz)	10	15.6	36	49.5	60

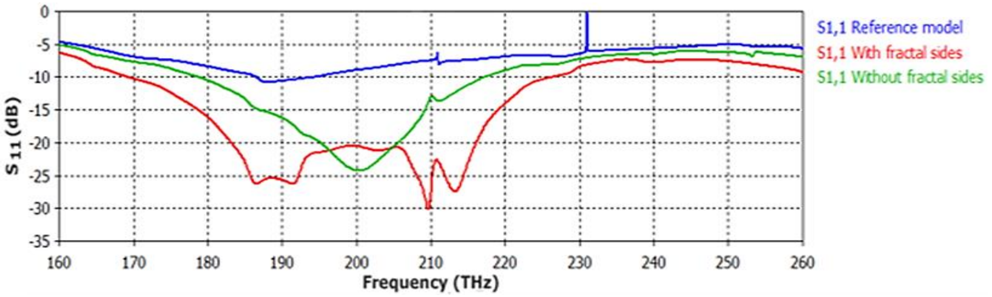


Figure 6. S11 for different model

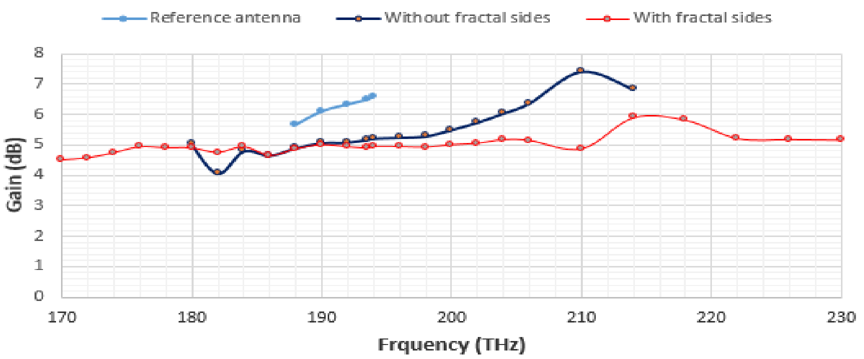
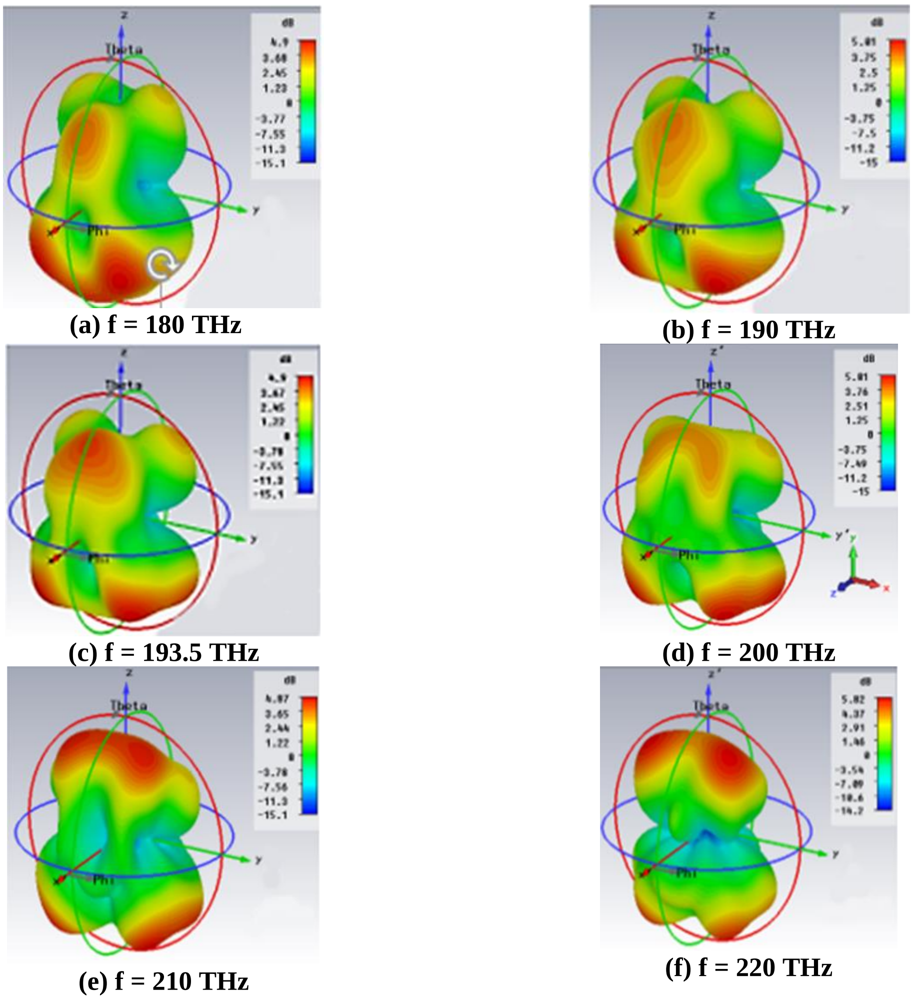


Figure 7. Plot of maximum gain versus frequency for the three different antenna models

5. CONCLUSION

The new model for hybrid plasmonic fractal patch nanoantenna was proposed to improve the bandwidth. The finite integration method (FIT) is used for simulation this antenna with CST microwave studio software. Also, the impedance bandwidth (S_{11} ≤-10dB) has been improved and the bandwidth increased from 36 THz (antenna geometry without fractal edge sides) to 60 THz at the final proposed model. A good consistent bi-directional broadside radiation pattern with a maximum gain up to 6 dB and 95% radiation efficiency has been obtained throughout the operational bandwidth.

APPENDIX



(a) f = 180 THz **(b) f = 190 THz**

(c) f = 193.5 THz **(d) f = 200 THz**

(e) f = 210 THz **(f) f = 220 THz**

Figure 8. 3-D Far-field gain plot for the proposed model, (a) f=180 THz, (b) f=190 THz, (c) f=193.5 THz, (d) f=200 THz, (e) f=210 THz, and (f) f=220 THz

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