Journal of Theoretical and Applied Information Technology
29th February 2012. Vol. 36 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

DESIGN AND FDTD MODELING OF MILLIMETER WAVE ANTENNA FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

This paper presents the design and finite difference time domain (FDTD) modeling of millimeter wave aperture coupled microstrip antenna that can be realized as a on chip antenna in wireless sensor nodes. At millimeter wave frequency, antenna form factor is very low and hence integration of this antenna with the transceiver components as a single system on-chip, minimizes power consumption and system cost. Off-chip antenna increases the size of the sensor node and raises the system cost. The proposed antenna contributes impedance bandwidth of 3 GHz (59 GHz – 62 GHz) and maximum gain of 6.8 dBi. The proposed antenna occupies an area of 1500 µm × 2000 µm on a RT Duroid substrate of dimension 3000 µm × 3000 µm × 1500 µm. Due to very low antenna form factor, the proposed antenna along with the transceiver and sensor components can be integrated into a single system on chip with less system cost for wireless sensor networks.

Keywords: *Finite difference time domain (FDTD), Microstrip Antenna, Sensor nodes, Ultrawideband, Wireless Sensor Networks (WSN).*

1. INTRODUCTION

Applications Wireless sensor network (WSN) consists of many energy autonomous micro sensors distributed throughout an area of interest. Many research works are carried in WSN to minimize communication protocol complexity and system cost [1-2]. As the sensor nodes consists of sensors, processing units, transceivers and antennas for sensing environmental physical parameters, processing the data to extract characteristics features of interest and transmitting them through wireless link, these subsystems can be integrated into a single system on chip to minimize power consumption, volume and system cost. The existing and emerging wireless systems such as WLAN, WPAN, UWB and Bluetooth operating below 11 GHz is likely to be congested in near future due to the lack of wide bandwidth. Broad frequency bands achieved at millimeter wave range not only satisfies increased number of channels but also provides simultaneous service of data, voice and video transmission at high data rates. Hence the need arises for the wireless system to move towards the millimeter wave frequency(>30 GHz) where the interference between the existing wireless systems can be completely eliminated. Millimeter wave band has many advantages such as large spectral capacity, reduced channel interference, compact antenna structure, light equipment, etc. and hence more attention is concentrated at 60 GHz that as 7 GHz (57-64 GHz) unlicensed spectrum [3-10]. Short wavelength and wide bandwidth at 60 GHz makes antenna structure compact [4] and microstrip antennas are suited for this application because of their conformal and low profile structure. It allows all the advantages of printed circuit technology and ease integration with millimeter wave circuits. WSN operating at millimeter wave frequencies leads to smaller size components including antenna with very small form factor and high directional gain which is highly desired. Moreover an off-chip antenna increases the size of the sensor node and raises the cost [11-12]. This paper presents the design and modeling of 60 GHz aperture coupled microstrip antenna which can be realized as a on chip antenna on transceivers of wireless sensor nodes.

2. METHODOLOGY

Antenna plays a vital role in wireless systems because it is traditionally off chip and occupies more area than the system size. For wireless sensor

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network it is desirable to have compact integrated system operating in millimeter wave range with antenna of small form factor. The proposed antenna satisfies the needs of wireless integration and provides ultrawideband required for high speed transmission. Figure. 1 shows the geometry of the proposed rectangular patch aperture coupled antenna realized on RT duroid of relative permittivity 2.17, and fed by 50 ohm microstrip line. As the size and geometry of aperture determines the amount of coupling and back radiation, the geometry of the aperture was chosen as a rectangular slot to minimize back radiation. The feed and antenna substrate thickness are chosen as 100 µm and 250 µm to suit for MMIC's applications. Table 1 shows the dimensions of the proposed antenna determined using transmission line model method for a resonant frequency of 61 GHz. With these design specifications the proposed antenna was modeled by FDTD technique and solved for antenna parameters using MATLAB.

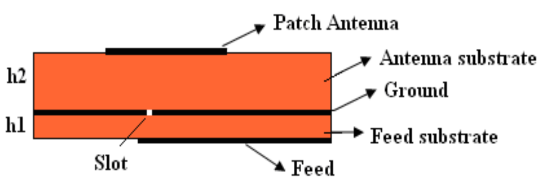

Figure 1 Geometry of Aperture coupled antenna

Table 1
Dimension of the proposed antenna

Antenna dimension parameter	Calculated value
Patch length	1.5mm
Patch width	2mm
Slot length	1mm
Slot width	0.375mm
Feed line Length	2mm
Feed line width	0.315mm

3. ANTENNA MODELING BY FDTD

The FDTD technique is a grid-based differential time-domain numerical modeling method [5]. FDTD algorithm solves Maxwell's time dependent curl equations by first filling the computational space by number of Yee cells (Figure. 2) and relative spatial arrangements of E and H fields on the Yee cell enable the conversion of Maxwell's equations into finite difference equations. That is the time-dependent Maxwell's equations in partial form given in equation (1) are discretized in space and time using central-difference approximations at time step n and space lattice point. The discretized field equations given in equation (2) are the updated equations used to compute the new field components from the field components at previous time steps. These equations are then solved in a time matching sequence by alternatively calculating the electric and magnetic fields in the interlaced spatial field.

$$\frac{\partial D_x}{\partial t} = \frac{1}{\sqrt{(\varepsilon\mu)}}\cdot\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right) \quad (1.a)$$

$$\frac{\partial D_y}{\partial t} = \frac{1}{\sqrt{(\varepsilon\mu)}}\cdot\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right) \quad (1.b)$$

$$\frac{\partial D_z}{\partial t} = \frac{1}{\sqrt{(\varepsilon\mu)}}\cdot\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) \quad (1.c)$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\sqrt{(\varepsilon\mu)}}\cdot\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right) \quad (1.d)$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\sqrt{(\varepsilon\mu)}}\cdot\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z}\right) \quad (1.e)$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\sqrt{(\varepsilon\mu)}}\cdot\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right) \quad (1.f)$$

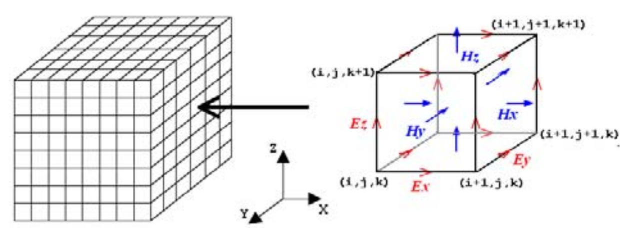

Figure 2 Discretization of the computational domain into Yee cell's for field computation

$$D_z^{n+\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right) = D_z^{n-\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right) + \left(\frac{\Delta t}{\Delta x c_0}\right)\left\{H_y^n\left(i+\frac{1}{2},j,k+\frac{1}{2}\right) - H_y^n\left(i-\frac{1}{2},j,k+\frac{1}{2}\right) - H_x^n\left(i,j+\frac{1}{2},k+\frac{1}{2}\right) + H_x^n\left(i,j-\frac{1}{2},k+\frac{1}{2}\right)\right\} \quad \ldots (2.a)$$

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$$H_z^{n+1}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)=H_z^{n+1}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)+\left(\frac{\Delta t}{\Delta x c_0}\right)\left\{E_y^{n+\frac{1}{2}}\left(i+1,j+\frac{1}{2},k\right)-E_y^{n+\frac{1}{2}}\left(i,j+\frac{1}{2},k\right)-E_x^{n+\frac{1}{2}}\left(i+\frac{1}{2},j+1,k\right)+E_x^{n+\frac{1}{2}}\left(i+\frac{1}{2},j,k\right)\right\} \quad \text{...(2.b)}$$

$$D_y^{n+\frac{1}{2}}\left(i,j+\frac{1}{2},k\right)=D_y^{n-\frac{1}{2}}\left(i,j+\frac{1}{2},k\right)+\left(\frac{\Delta t}{\Delta x c_0}\right)\left\{H_x^{n}\left(i,j+\frac{1}{2},k+\frac{1}{2}\right)-H_x^{n}\left(i,j+\frac{1}{2},k-\frac{1}{2}\right)-H_z^{n}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)+H_z^{n}\left(i-\frac{1}{2},j+\frac{1}{2},k\right)\right\} \quad \text{... (2.c)}$$

$$H_y^{n+1}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)=H_y^{n+1}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)+\left(\frac{\Delta t}{\Delta x c_0}\right)\left\{E_x^{n+\frac{1}{2}}\left(i+\frac{1}{2},j,k+1\right)-E_x^{n+\frac{1}{2}}\left(i+\frac{1}{2},j,k\right)-E_z^{n+\frac{1}{2}}\left(i+1,j,k+\frac{1}{2}\right)+E_z^{n+\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right)\right\} \quad \text{.. (2.d)}$$

$$D_x^{n+\frac{1}{2}}\left(i+\frac{1}{2},j,k\right)=D_x^{n-\frac{1}{2}}\left(i+\frac{1}{2},j,k\right)+\left(\frac{\Delta t}{\Delta x c_0}\right)\left\{H_z^{n}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)-H_z^{n}\left(i+\frac{1}{2},j-\frac{1}{2},k\right)-H_y^{n}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)+H_y^{n}\left(i+\frac{1}{2},j,k-\frac{1}{2}\right)\right\} \quad \text{.. (2.e)}$$

$$H_x^{n+1}\left(i,j+\frac{1}{2},k+\frac{1}{2}\right)=H_x^{n+1}\left(i,j+\frac{1}{2},k+\frac{1}{2}\right)+\left(\frac{\Delta t}{\Delta x c_0}\right)\left\{E_z^{n+\frac{1}{2}}\left(i,j+1,k+\frac{1}{2}\right)-E_z^{n+\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right)-E_y^{n+\frac{1}{2}}\left(i,j+\frac{1}{2},k+1\right)+E_y^{n+\frac{1}{2}}\left(i,j+\frac{1}{2},k\right)\right\} \quad \text{.. (2.f)}$$

To suppress the numerical dispersion in the computational domain, the spatial discretized component Δx, Δy and Δz must be less than λ/10. For the model to be stable, the time increment Δt must obey the stability criterion given in equation (3).

$$\Delta t=\frac{1}{\frac{1}{\sqrt{\varepsilon\mu}}\times\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}}} \quad \text{.. (3)}$$

The first step to design an antenna is to grid up the computational domain created based on the antenna dimension. The computational domain for the proposed antenna is chosen as a rectangular grid of size 3mm × 3mm × 1.5mm in x, y and z directions respectively (Table 1). To suppress the numerical dispersion in the computational domain, minimum wavelength to cell dimension ratio is chosen as 20. Hence the size of the uniform cell in the computational domain is 25µm × 75µm × 50µm. This results in 144000 cells in 3D domain with 120 cells along x direction, 40 in y direction and 30 in z direction. Once the grid size is chosen, the time step is determined such that numerical instabilities are avoided, according to the stability condition.

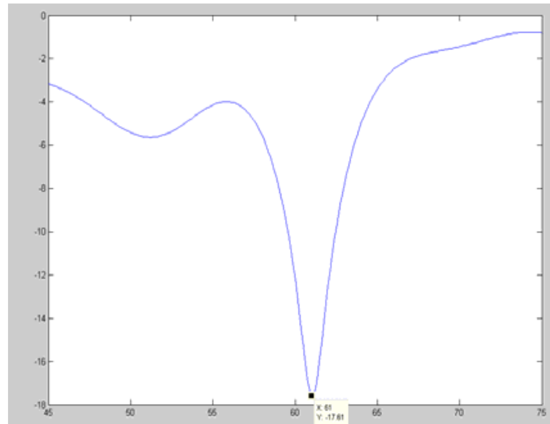

Figure. 3 Return loss characteristics of the proposed antenna by FDTD method

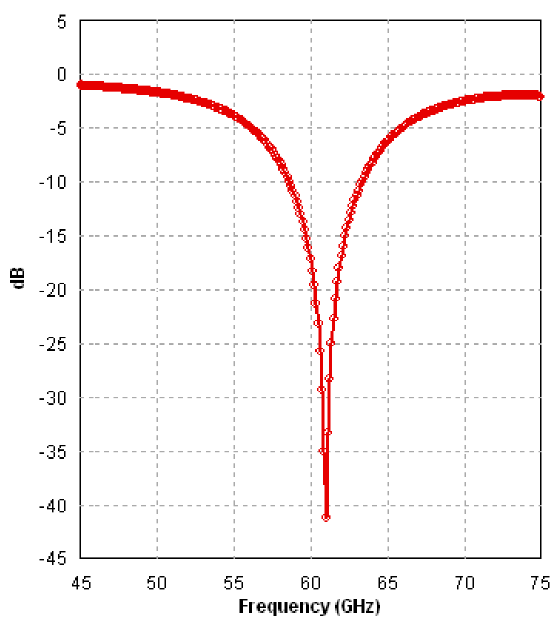

Figure. 4 Return loss characteristics of the proposed antenna

4. RESULTS AND DISCUSSION

Electric and magnetic fields in each cells were determined for Gaussian source excitation and updated for frequency span of 45 to 75 GHz. In order to determine the input reflection coefficient of the antenna, the incident and reflected voltages were calculated. Computed return loss as a function of frequency is shown in Figure 3. It depicts that the impedance bandwidth is 3 GHz with a return loss of -17.2 dB at resonant frequency of 61 GHz.

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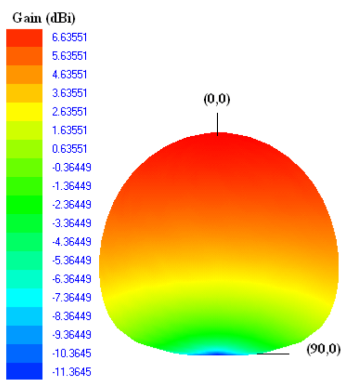
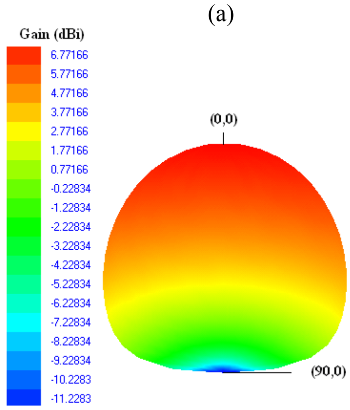
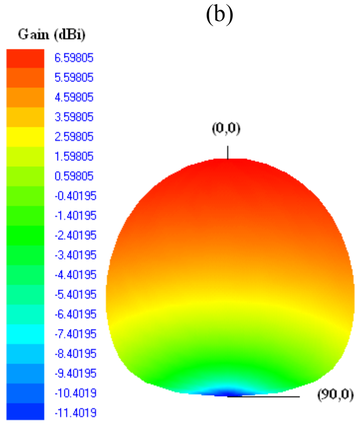
The proposed antenna was also simulated using IE3D software to study return loss and radiation characteristics to validate the mathematical modeling technique. Figure. 4 shows the simulated return loss characteristics of the proposed antenna with impedance bandwidth of 4.757 GHz and radiation characteristics is consistent within the operating band with negligible back radiation (Figure 5). Return loss characteristics computed by FDTD method is in good agreement with the simulation results (Figure.6). Table 2 gives the comparison of FDTD and simulation results.



(a)



(b)



(c)

Figure. 4 3D radiation pattern of the proposed antenna at (a) 60 GHz, (b) 61 GHz and (c) 63 GHz

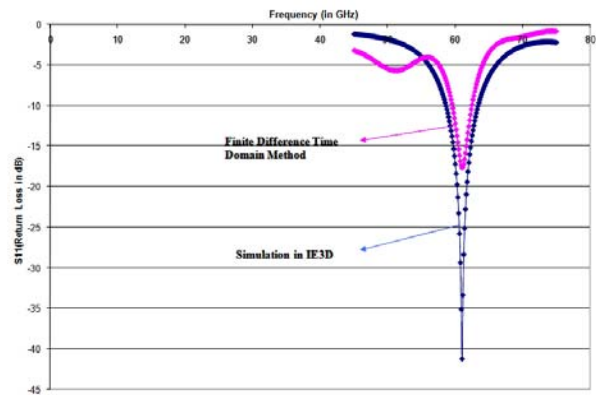


Figure. 6 Comparison of FDTD and simulation results of the proposed antenna.

Table 2
Comparison of FDTD and simulation results

Antenna parameter	Simulation Results	FDTD Results
Resonant frequency	61 GHz	61 GHz
Return loss	-41.2 dB	-17.61dB
Bandwidth	4.757 GHz	3 GHz

5. CONCLUSION

The Mathematical modeling of an aperture coupled patch antenna at 61 GHz is done using FDTD Method. The computed results are in good agreement with the simulated results and hence FDTD modeling technique can be applied for various microwave circuits at millimeter wave frequencies to study the performance characteristics in an ease manner. As the proposed antenna contributes wide bandwidth with small form factor, it can be realized as an on chip antenna for wireless sensor networks system assigned for high rate data transfer. The antenna can also be realized in array configuration to improve its gain characteristics.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

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