



Design of a wideband microstrip nanoantenna array

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Abstract

This paper presents the design of a logarithmic array of microstrip nano-antennas at terahertz frequencies. For applications in which small antennas are required, microstrip antennas are preferred. However, they have a narrow bandwidth. To overcome this problem in microstrip antennas, a log-periodic nanoantenna design is presented which exhibits a wide bandwidth and ultra-compact design. This antenna is smaller in size compared to log-periodic antennas in microwave bands and comparable and better radiation characteristics. The proposed Log-periodic microstrip nanoantenna array consists of seven patch elements on a dielectric layer and are fed directly by a feed line through the branch lines connected to each of the elements. Scaling factor, $\tau = 0.95$ is considered for this design and inset feed is used. In this structure, the substrate has a relative dielectric constant of $\epsilon_r = 4.4$ and a thickness of $h = 800$ nm. For good performance at high frequencies, gold is used for the design of the antenna. The considered operating frequency is 3.3 THz corresponding to a wavelength of $91 \mu\text{m}$. Good impedance matching and a wide bandwidth of 800 GHz is obtained.

Keywords Log-periodic · Nanoantenna array · Wideband · Microstrip

1 Introduction

Microstrip antennas are popular due to their advantages, such as low fabrication cost, integrability with electronic devices and small size. However, their narrowband performance limits their applications in most systems. In order to compensate for such a disadvantage, various structures have been proposed, such as monopole, quasi-Yagi and Vivaldi antennas (Liang et al. 2005). Application of a log-periodic structure to antenna configuration may lead to 50% increase in bandwidth together with a stable radiation pattern (Hall 1980). In microwaves, various potential antenna designs are considered, which include variable size patches, patches with variable slot lengths, and patches with fixed slot fed by a variable

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length stripline. In the terahertz band, however, less research is done on antennas (Ahmadi et al. 2010). There have been improvements, recently, to increase the bandwidth of microstrip antennas. In Azizi et al. (2017), by using graphene in terahertz frequencies, bandwidth is increased from 20 to 40 GHz. In order to increase the bandwidth of microstrip antennas, Meta-Material Split Ring Resonator Radome is used (Sharifi and Khalilpour 2015). Another simple and common way to increase the bandwidth is increasing the thickness of the substrate. The disadvantage of this method is increased loss due to surface waves (Luther et al. 2014). Common methods such as decreasing the permeability of the substrate are effective in increasing bandwidth, but these methods increase the weight and cross section of the antenna (Almutawa and Mumcu 2013). Other wideband structures for nanoantennas are also presented. For example, a 2×2 cavity-backed slot antenna array with a corrugated surface operated at 1 THz has been designed that exhibits a 250 GHz bandwidth (Luk et al. 2017).

Using a log-periodic microstrip array (LPMA) is an effective way to compensate for the narrow bandwidth of microstrip antennas. On the other hand, due to the increasing need to provide miniaturized devices at very high frequencies, the implementation of nanotechnology is inevitable. Therefore, the present work is done at terahertz frequencies.

A transmission line is used as the feed line with a 180° phase reversal between adjacent elements. The patches are connected to the feed line in parallel. Log-periodic antennas are generally wideband antennas and the dimensions are characterized by the scaling factor. The position of the dipoles is obtained using the spacing factor. The dipoles of the antenna can be replaced by patches or other appropriate elements (Li et al. 2016; Guan et al. 2016; Rashed-Mohassel 1989).

In this paper, a log-periodic microstrip nanoantenna array with inset feed is analyzed and is designed at terahertz frequencies. The structure is designed by CST software. Besides, for comparison, simulation with HFSS software is performed as well. The design procedure and the results are given in sections two and three, respectively. The paper is concluded in the fourth section.

2 Antenna analysis and design

The proposed Log-periodic microstrip nanoantenna array consists of seven patch elements on a dielectric layer and are fed directly by a feed line through the branch lines connected to each of the elements. The dimensions of the elements and their spacings increase from the feeding point with appropriate scaling and spacing factors as in the design of log-periodic antennas. Since, it is difficult to obtain an impedance matching for more than two elements using a corporate feed, the serial feed is used for individual elements of the array. The inset feed is used for impedance matching purposes. Figure 1 illustrates a microstrip patch element as the basic element for the design of the array.

In this design, the substrate has a relative dielectric constant of $\epsilon_r = 4.4$ and a thickness of $h = 800$ nm. For good performance at high frequencies, gold is used for the design of the antenna. The resonant frequency of the structure is 3.3 THz. The characteristic impedance of the microstrip feed line structure is considered to be 50Ω . Since for a favorable design, thicknesses of patches, feed lines and ground plane should be much smaller than

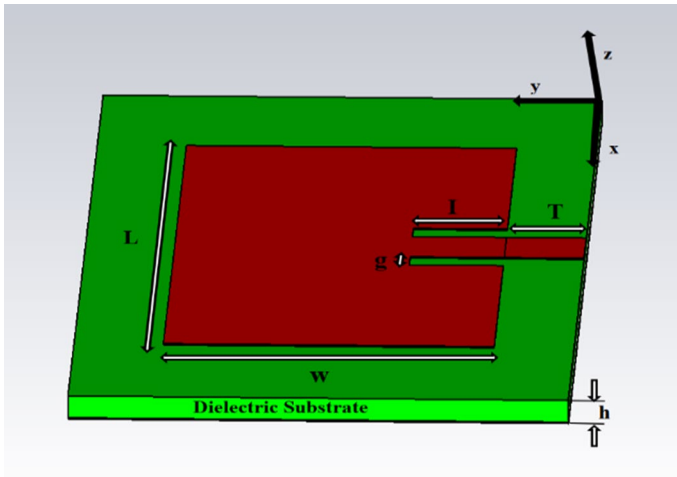


Fig. 1 The basic element of the log-periodic microstrip array

the wavelength in free space (Balanis and Theory 2005; Bancroft 2009), the thickness is considered to be 50 nm. The inset feed that is used in this array, distributes power directly between each element.

The design procedure of the basic patch starts with finding the effective relative permittivity of the structure, ϵ_{reff} , given by (1) and incorporating the fringing fields, using the well-known effective length, L_{eff} , (Balanis and Theory 2005)

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\left(1 + 12 \frac{h}{w}\right)^{\frac{1}{2}}} \frac{w}{h} > 1 \tag{1}$$

$$\Delta L = 0.412h \frac{\epsilon_{reff} + 0.3 \left(\frac{w}{h} + 0.264\right)}{\epsilon_{reff} - 0.258 \left(\frac{w}{h} + 0.8\right)} \tag{2}$$

$$L_{eff} = L + 2\Delta L \tag{3}$$

where, L_{eff} is the effective length of the patch.

In the design of microstrip antennas, choosing the patch width, w , is crucial. For small values of w , antenna efficiency reduces and for large values, higher order modes will appear. Therefore, an optimal patch width should be selected (Balanis and Theory 2005):

$$w = \frac{\lambda_0}{2} \left(\frac{\epsilon_r + 1}{2}\right)^{\frac{-1}{2}} \tag{4}$$

$$L = \frac{1}{2f_r \sqrt{\mu_0 \epsilon_0} \sqrt{\epsilon_{reff}}} - 2\Delta L \tag{5}$$

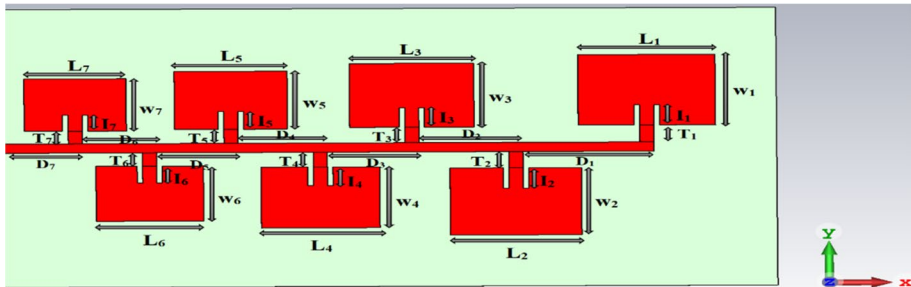
The characteristic impedance of the microstrip feed line is also obtained from (6) (Balanis and Theory 2005):

$$z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_{reff}}} \ln \left[\frac{8h}{w} + \frac{w}{4h} \right] & \frac{w}{h} \leq 1 \\ \frac{120\pi}{\epsilon_{reff}} \left[\frac{w}{h} + 1.393 + 0.667 \ln \left(\frac{w}{h} + 1.444 \right) \right] & \frac{w}{h} > 1 \end{cases} \quad (6)$$

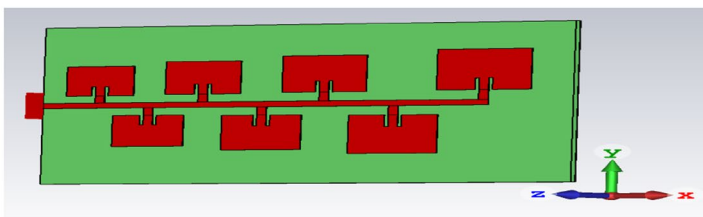
In which, w and h are the width of the patch and the height of the substrate, respectively.

In these equations, ϵ_0 and μ_0 are constant and λ_0 and h are determined using the wavelength associated with the resonant frequency. In fact, the only parameter that can be affected by high frequencies is ϵ_r which consequently affects w and L . Since the substrate thickness is small enough and our design frequency is much less than 20 terahertz, dispersion can be ignored and it does not have a significant effect on the results and design validity. However, it can marginally affect efficiency and losses of the antenna (Lourtioz 2015; Costa et al. 2011; Prokopidis and Tsioukakis 2006). On the other hand, ϵ_r for metals can vary at high frequencies due to dispersion and it is necessary to use models such as Drude model. However, it should be noted that this occurs at frequencies above 20 terahertz (Luk et al. 2017; Lourtioz 2005). Our design is at 3.3 THz (far infrared), and according to our simulations the variations of ϵ_r in this frequency is not considerable and dispersion can be ignored (Luk et al. 2017). Figure 2 illustrates the geometry of the designed log-periodic microstrip patch antenna.

The geometrical configuration of a log-periodic array is given in terms of design parameters τ , σ and half the apex angle, α is given by (Balanis and Theory 2005)



(a)



(b)

Fig. 2 Log-periodic microstrip patch antenna array with inset feed. **a** Front, **b** 3D view

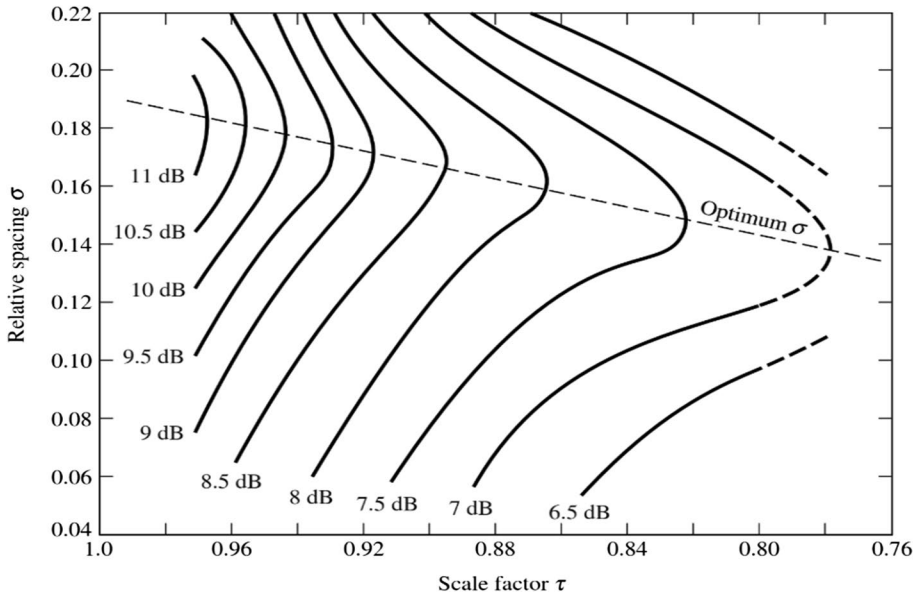


Fig. 3 Contours of constant directivity versus σ and τ (Balanis and Theory 2005)

$$\alpha = \tan^{-1} \left[\frac{1 - \tau}{4\sigma} \right] \quad (7)$$

where, σ is the spacing factor, τ is the scaling factor and 2α , the apex angle, is the angle made by straight lines connecting the elements ends.

In this design, a directivity of 8 dB is contemplated. From the classic constant directivity curves, (Fig. 3) the scaling factor, τ , is normally within 0.7 to 0.95 (Balanis and Theory 2005), from which $\tau=0.95$ is selected. According to these curves and given $\tau=0.95$ and 8 dB for the directivity, the spacing factor, σ , is obtained as 0.05.

Using the conventional design formulas of patch antennas and with $\epsilon_r=4.4$ and $\lambda=91 \mu\text{m}$, the length and width of the patch antenna as well as the feed line width are obtained. Software's optimization is also used to optimize w and L . Inset feed is used for impedance matching of the patch to main feed line, in which the length and width of inset feed and gaps are determined using design formulas (Balanis and Theory 2005). The width of inset feed gap is considered fixed, equal to $1.2 \mu\text{m}$. The initial value of the separation between the elements, $D1$, is also obtained using the software optimization module. Using the microstrip antenna design equations, the width of the feed line is found to be $3 \mu\text{m}$. The thickness of the patches is considered to be 50 nm and the dimensions of structure are $168 \mu\text{m} \times 90 \mu\text{m} \times 0.9 \mu\text{m}$.

The optimal spacings between the elements were determined for least coupling effects. In general, optimization by CST is used to obtain best gain and impedance matching, as well. As for the array, the dimensions and spacings of other patches are obtained using the scaling factor, $\tau=0.95$, and the known formula (8) (Balanis and Theory 2005). Finally, these parameters are listed in Table 1.

Table 1 Parameters of the designed log-periodic microstrip nanoantenna array

Element number	W (μm)	L (μm)	T (μm)	I (μm)	D (μm)
1	21.22	27.64	5.50	7	28
2	20.16	26.26	5.22	6.65	26.60
3	19.15	24.94	4.96	6.31	25.27
4	18.19	23.69	4.71	6	24
5	17.28	22.51	4.48	5.70	22.80
6	16.42	21.38	4.25	5.42	21.66
7	15.59	20.31	4.04	5.14	20.57

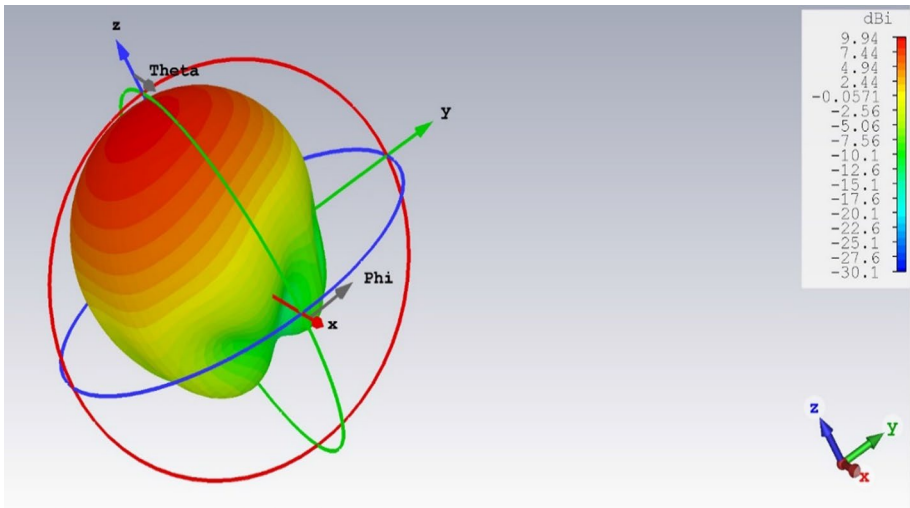


Fig. 4 Radiation pattern of the antenna

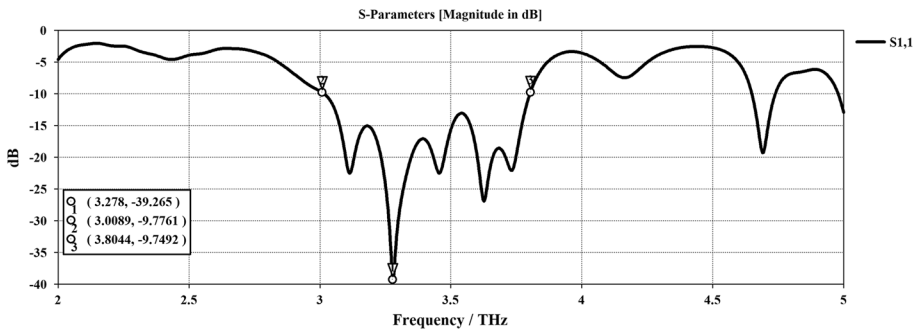


Fig. 5 S₁₁ plot

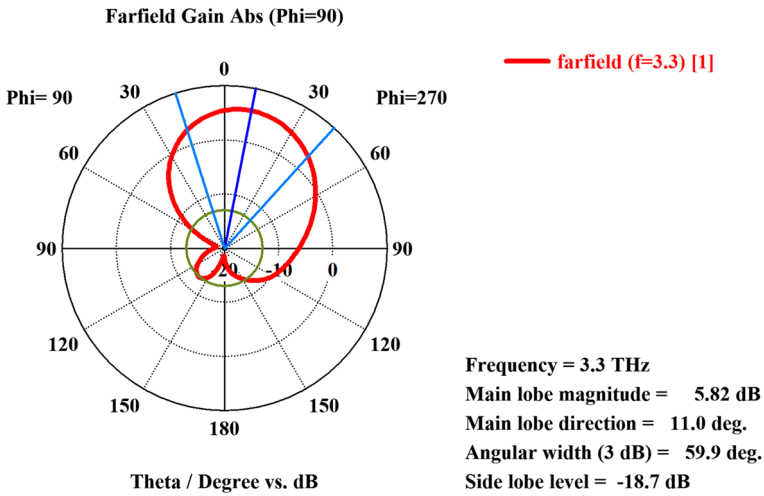


Fig. 6 Polar plot of the gain at 3.3 THz

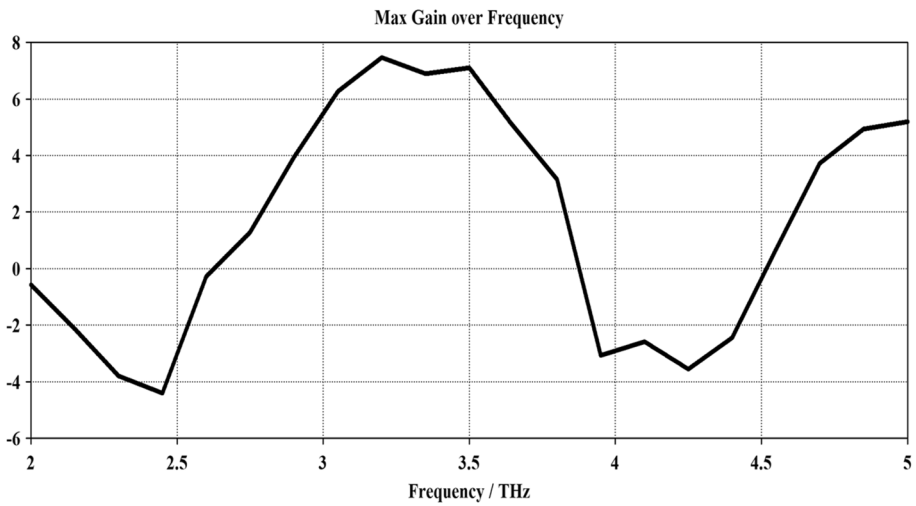


Fig. 7 Gain of the antenna versus frequency

$$\tau = \frac{W_{n+1}}{W_n} = \frac{L_{n+1}}{L_n} = \frac{T_{n+1}}{T_n} = \frac{I_{n+1}}{I_n} = \frac{D_{n+1}}{D_n} \tag{8}$$

3 Results

In simulation, the intended directivity of 9.94 dBi was achieved which meets the desired value of 8 dB. Radiation pattern of the antenna is illustrated in Fig. 4.

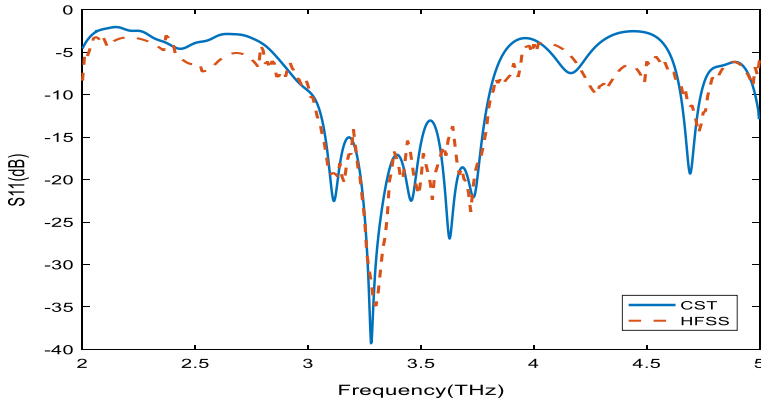


Fig. 8 S11 versus frequency by CST and HFSS

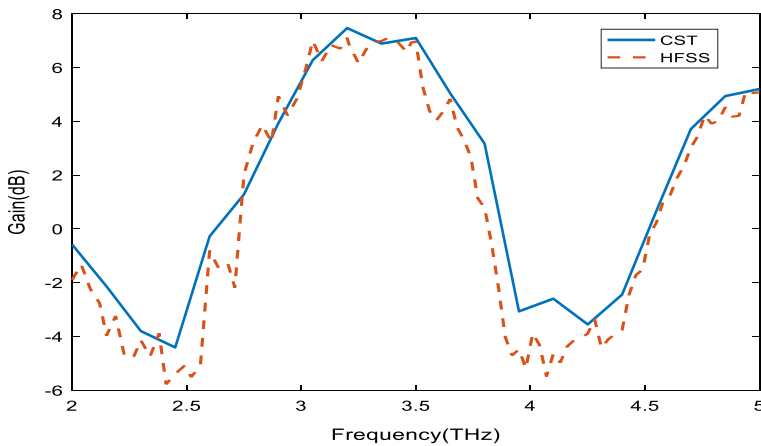


Fig. 9 Gain versus frequency by CST and HFSS

The reflection coefficient of the array is shown in Fig. 5. A broad bandwidth of 800 GHz corresponding to -10 dB and a dip of -40 dB is observed at the operating frequency.

The associated VSWR corresponding to the 800 GHz bandwidth, is less than 2 and VSWR = 1.03 at resonant frequency. The gain of the antenna is approximately 6 dB at 3.3 THz with a main lobe in $\theta = 11^\circ$ and $\varphi = 90^\circ$. Polar plot of gain is illustrated in Fig. 6. The gain of the antenna for the entire frequency range of 2–5 GHz is plotted in Fig. 7. The gain of the antenna remains above 6 dB over the entire bandwidth.

In addition to CST simulation, the design was simulated with HFSS as well. A comparison between S11 and gain results of the two softwares are illustrated in the Figs. 8 and 9 respectively. As is observed, good agreement exists and both results follow the same trend.

4 Conclusion

In this paper, a log-periodic microstrip nanoantenna array at terahertz frequencies is presented for wideband applications. The smallest dimension in structure is 100 nm. The obtained results yields good impedance matching with $S_{11} = -40$ dB and $VSWR = 1.03$ at 3.3 THz. A broad bandwidth of 800 GHz is achieved with a maximum gain of 6.8 dB over this frequency band. The proposed design is simulated by CST and HFSS softwares. Both results follow the same trend and are in good agreement.

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