# Performance Enhancement of Millimeter Wave Antenna with Integrated Inter-digital Capacitor Structure

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Abstract. In this paper, we present an approach for performance enhancement of an antenna for millimeter wave (mmWave) applications. From mmWave band, a 30 GHz frequency is selected for designing a patch antenna as it is suitable for the number of applications. Then the designed antenna is modified by inserting a capacitive structure i.e., inter-digital capacitor (IDC) for better impedance matching. Insertion of IDC structure results in antenna size reduction along with the increased directivity and enhancement in gain. Similarly, this technique is capable of providing extra resonance with an advantage of fine tuning, as it offers control over both resonating frequencies independently. Further, a linear antenna array is designed with the same approach for mutual coupling analysis. From the results, it has been found that this technique is also capable of providing mutual coupling mitigation. Thus insertion of IDC structure provides overall performance enhancement in mmWave antenna.

## **Keywords**

Millimeter wave antenna, dual-band characteristics, performance enhancement, capacitive loading

## 1. Introduction

Over the last decade, there have been conspicuous advances in the field of wireless communication, most of the wireless applications use ultra & super high frequency bands. This escalating demand has resulted in saturation of the available bands thus leading to diminution on the available bandwidth as well as data rate. An approach to use the frequency bands which are unexploited and are available for various applications is highly desirable to overcome the aforesaid problem.

Millimeter wave (mmWave) technology works on the frequency band ranging from 30 GHz to 300 GHz. For mmWave frequency, the size of the antenna required is very small thus resulting in smaller ranges for communication. To overcome this problem antenna must be used in an array so that overall gain can get increased along with the range [1]. Though mmWave frequency spectrum is unutilized, researchers are exploring it for various applications like body centric communication [2], detection of concealed threats [3] and 5G communication [4]. Above discussed applications require antenna with characteristics like

- Higher gain for high penetrating capabilities.
- Compact dimensions to have less mutual coupling.
- Narrow bandwidth.
- Highly directive for efficient area coverage.
- Multiband.

There are few techniques available in literature which improve any one of the above mentioned characteristics, like use of hybrid substrate or superstrate layer for antenna fabrication for gain enhancement [5]; use of various structures like electromagnetic band gap structures between the array elements for suppression of surface-wave for mutual coupling reduction [6]; approach of using parasitic shorting strips for antenna size reduction [7]. Further, there are few techniques which can simultaneously improve any two of the above characteristics like the use of a defected ground plane for mutual coupling reduction [8] and multiband resonance [9]. Similarly, metamaterial or composite right/left handed (CRLH) material is also considered for achieving improvement in two or more characteristics of the antenna. As mentioned in [10] metamaterial is used in an antenna for miniaturization and mutual coupling improvement; also in [11] size reduction along with multiband resonance is procured using metamaterial structure. Alternatively, a fractal tree structure is another approach by which miniaturization can be achieved along with the multiband characteristics [12].

All these techniques are difficult for fabrication and often impractical for a dedicated application. Similarly, implementation of any of these technologies results in improvement of either one or two characteristics of an antenna at a time. But, it is very challenging to improve all the above discussed characteristics of an antenna simultaneously. Hence in this paper, we propose an approach by which all the characteristics of an antenna are improved for achieving the application requirement. Similarly, after acquiring dual band characteristics by this approach, the resonances in a dual band can be altered individually. This unique capability of fine tuning makes designing of antenna flexible in terms of resonance and bandwidth.

The organization of this paper is as follows: Section 2 presents the design methodology and results of the patch antenna with and without IDC for 30 GHz. From the range of mmWave band, a 30 GHz frequency is selected for the antenna design as it is suitable for the number of applications [2], [13]. Similarly discussion includes basics of inter-digital capacitor (IDC). Section 3 presents analysis of fine tuning after insertion of IDC structure on antenna. Section 4 gives comparison of results obtained from both the antenna designs along with the existing antenna in literature. Section 5 presents array analysis for verifying the mutual coupling between the antennas and finally conclusions from obtained results are drawn in Sec. 6. All antennas discussed in this paper are designed and simulated using HFSS software.

## 2. IDC-based Antenna Design Methodology

For designing of this antenna we have started with the designing of edge feed rectangular patch antenna as an initial stage and then same designed antenna is modified by loading inter-digital capacitor (IDC) structure in it.

#### 2.1 Patch Antenna Design

The rectangular patch antenna is designed for the resonant frequency of 30 GHz as an initial stage. The standard antenna equations mentioned in [14] are used for calculating the various dimension of the rectangular patch. Then, dimensions are optimized for impedance matching at the desired frequency. The substrate size is  $15 \text{ mm} \times 12 \text{ mm} \times 0.8 \text{ mm}$  with top surface consisting of a rectangular patch of dimensions  $5.9 \text{ mm} \times 3.25 \text{ mm}$  and full ground plane at the bottom as shown in Fig. 1(a). The antenna is fed with a microstrip line of width 2.38 mm with edge feed of width 1.6 mm resulting in an impedance match of 50  $\Omega$  and the substrate used is Rogers RT duroid 5880 with a dielectric constant  $\varepsilon_r = 2.2$ , loss tangent (tan $\zeta$ ) = 0.0009 and copper thickness  $= 60 \,\mu\text{m}$ . Two hole panel mount K type connector is used to feed input signal which supports frequency range from DC to 40 GHz. The fabricated patch antenna design is shown in Fig. 1(b).

To check the impedance matching of the designed patch antenna, Smith chart has been plotted as shown in Fig. 1(c). Ideally, at the point of resonance, the impedance plot in Smith chart should touch its center i.e. (1,0) location. We can conclude from Fig. 1(c) that the antenna terminal impedance is not matching properly as the plot is away from the real axis of the Smith chart. The impedance of an antenna at 30 GHz comes out to be 48 + 11j. To move the impedance plot further towards the real axis we



Fig. 1. (a) Designed patch antenna. (b) Fabricated patch antenna. (c) Smith chart of patch antenna with marker showing impedance at 30 GHz. (d) Surface current distribution at 30 GHz.

must compensate the imaginary component of antenna impedance. As the reactance part in antenna impedance is positive, to compensate we must introduce a series capacitance into the antenna. Insertion of the inter-digital capacitor structure to feed line provides good impedance matching which results in the reduction in the size of an antenna [15]. So, similar IDC structure is inserted but onto the patch surface instead of the feed line.

#### 2.2 IDC Structure Basics

The inter-digital capacitor (IDC) structure is a multifinger planer structure where the narrow gap between the fingers gives capacitance. The structure is designed in such a way that it can be accommodated in a small area. The observed value of quality factor in case of IDC is comparatively higher than that of MIM capacitor and gap capacitor. The IDC structure has four parameters i.e. the number of fingers N, width of the fingers W, gap between the consecutive fingers G and length of the finger L. The capacitance generated due to the structure changes depending upon the value of these parameters. The value of capacitance is directly proportional to the width, length and number of fingers and inversely to the gap between consecutive fingers. Figure 2(a) shows the design of IDC having 10 fingers.

To obtain optimum finger width value for the IDC structure, an empirical analysis is performed. Figure 2(b) shows the effect of variation of finger width from 0.1 mm

to 0.2 mm with respect to peak gain and half power beam width (HPBW). It is observed that the increase in the finger width results in an increment in peak gain while decrementing in HPBW. So for inserting the IDC structure, the optimized value for the width of the finger is considered as 0.15 mm. Note that even though the value of peak gain is increasing with a finger width, the losses corresponding to an antenna are also increasing, which results in a lower value of radiation efficiency.

#### 2.3 Antenna Design using IDC

The above mentioned IDC structure is inserted in the patch by creating a slot. After addition of the IDC structure, the response of the antenna was studied again; in which it has been found that the resonant frequency of the antenna has changed from 30 GHz to 29.25 GHz. Hence to shift the resonant frequency back to 30 GHz dimensions of the patch are altered. The patch dimensions for matching 30 GHz resonance comes out to be  $5.6 \text{ mm} \times 3.1 \text{ mm}$ . The dimensions of the designed patch antenna after insertion of IDC are shown in Fig. 3(a). It has been found that resonant frequency of the IDC depends on the combination of number of fingers, width of the finger and gap between the fingers. So, for better results in terms of reflection



Fig. 2. (a) Interdigital capacitor structure. (b) Effect of variation of finger width with respect to peak gain and HPBW for 30 GHz frequency.





Fig. 3. (a) Designed patch antenna with IDC. (b) Fabricated IDC based patch antenna. (c) Reflection coefficient graph. (d) Surface current distribution at 30 GHz. (e) Measured and simulated 2D radiation pattern of patch antenna with and without IDC for 30 GHz frequency in xz-plane (φ = 0°) and (f) yz- plane (φ = 90°).

coefficient at 30 GHz frequency, values of IDC parameters come out to be N = 8, with W = 0.15 mm, G = 0.5 mm and L = 1.5 mm.

Addition of IDC structure results in improvement of the reflection coefficient from -19 dB to -29 dB which signifies better matching of the antenna for the desired frequency. The fabricated antenna designed using IDC

structure is shown in Fig. 3(b). Figure 3(c) shows the reflection coefficient response of simulated and measured results of the patch with and without IDC structure. It is observed that simulated and measured results are in good agreement. Surface current distribution of the designed antenna with IDC at 30 GHz is shown in Fig. 3(d). Simulated and measured radiation pattern of the patch antenna with and without IDC in xz-plane and yz-plane can be observed from Fig. 3(e) and (f), respectively. We can conclude from Fig. 3(f) that the radiation pattern after insertion of IDC structure becomes narrower compared to the normal patch case which results in an increment of peak gain. Hence, the increased value of peak gain is due to the narrowing of the main lobe which makes energy radiated by an antenna more concentrated in the main lobe direction.

#### 2.4 Capacitive Effect in IDC

The  $\pi$  type transmission line model of IDC structure based antenna is shown in Fig. 4. The metal surface of patch and ground plane can be considered as a two wire transmission line model with the distributed series inductance  $L_{\rm R}$  and distributed shunt capacitance  $C_{\rm R}$  which are associated with the permeability and permittivity of the substrate respectively. Similarly, the dielectric conductivity of the substrate can be modelled as shunt inductance  $L_{\rm L}$ . Usually, the value of shunt inductance remains very small and can be neglected for few particular cases. Inserted IDC structure can be modelled as the series capacitor  $C_{\rm L}$  along the patch. Other circuit components are not considered in this discussion as the value of those components depends on the substrate and patch properties which are same for both designs. For IDC structure, the capacitor  $C_{\rm L}$  can be represented by the combination of three capacitances involved in the design. As shown in Fig. 2 (a)  $C_1$  is the capacitance because of the two extreme fingers with the elements present on the outer side of the IDC along the length of the patch.  $C_2$  is the capacitance because of the gap near the tip of the finger along the width of the patch. Similarly,  $C_3$  is the capacitance along the length because of the two adjacent fingers. Hence, the overall value of the capacitance  $C_{\rm L}$  because of the IDC structure having N fingers can be given by:

$$C_L = C_1 + NC_2 + (N-2)C_3.$$
(1).

There are different approaches in the literature for calculation of  $C_1$ ,  $C_2$  and  $C_3$ . Similarly, there are few assumptions for optimization like mutual capacitance is con-



**Fig. 4.**  $\pi$  type transmission line model of the design [16].

sidered in adjacent fingers only and capacitance  $C_2$  is neglected due to the lower value, etc. The representation of interdigital capacitor structure is described with its corresponding subcomponents in [17]. The computation of capacitance value is essential for the practical realization of the structure and for deriving lumped equivalent circuit model.

### 3. Analysis

To understand the impact of insertion of IDC structure, an analysis is performed with respect to reflection coefficient. It has been observed that the insertion of IDC results in giving an extra resonance. If this resonance matches with the resonance generated by patch then there will be only one resonance corresponding to that antenna. But in all other cases, insertion of IDC will give an extra resonance. Initially, capacitance generated by the IDC structure has been changed by changing the width of the finger and keeping patch dimensions as it is. Figure 5(a)gives the variation of reflection coefficient by changing finger width W gradually from 0.1 mm to 0.2 mm. All other parameters are kept same throughout the analysis, patch length is kept as 3.4 mm, N = 4, G = 0.7 mm and L = 1.5 mm. Here increment in the width of finger resulted in an increase of capacitance and the increased capacitance



Fig. 5. (a) Variation in IDC structure keeping patch dimensions constant. (b) Variation in patch length keeping IDC structure constant.

shifted the resonant frequency towards left. The variation in IDC structure results in the change of resonant frequency corresponding to IDC resonance while keeping the patch resonance as almost constant. To verify the above analysis, now the IDC structure has been kept constant with N = 4, G = 0.7 mm, L = 1.5 mm and W = 0.15 mm while the length of the patch has been varied from 3 mm to 3.5 mm. In this case, patch resonance has changed while the IDC resonance is almost constant as shown in Fig. 5(b). To get single resonance at any desired frequency, the combination of IDC and patch length must be varied in such a way that overall generated capacitances give only one resonant peak.

The main challenge in designing dual band antenna is to get resonating bands exactly at the required frequencies. For various applications with dual band antenna, we can insert capacitive structure as it will provide additional resonance with an advantage of control over both the resonating frequencies. We can alter either of the resonating frequencies without changing the other, so this can be considered as tuning technique for matching resonances in the multiband antenna. This can be observed from Fig. 5(a) and Fig. 5(b) that two resonances can be varied by either changing IDC structure or changing the length of a patch. This multiband property can be used for designing a Kaband satellite communication antenna with an uplink of 28 GHz–30 GHz and downlink of 18 GHz–20 GHz.

## 4. Comparison of Results

We can observe from Tab. 1 that insertion of IDC in patch antenna results in the reduction of patch dimensions along with the advantage of better matching. Usually, insertion of reactive structure on patch antenna increases the Q factor which results in bandwidth reduction. So we can observe from Tab. 1 that the bandwidth got reduced after insertion of IDC structure. It can be observed from Fig. 1(d) that the majority of the surface current flows through the boundary of the patch which results in a broader radiation pattern for the normal patch antenna. On the other hand, it can be observed from Fig. 3(d) that the majority of current

Parameters	Patch w/o IDC	Patch with IDC	[18]
Antenna dimensions (mm)	15 × 12	14×11.7	19 × 17
Patch dimensions (mm)	5.9 × 3.25	5.6 × 3.1	3.9 × 3.24
S11 at 30 GHz (dB)	-19 (-32)	-29 (-47)	-32 (-28)
Peak gain (dB)	6.89 (5.9)	8 (7.2)	8.47
Bandwidth (GHz)	6 (7.5)	3 (4.4)	2 (2)
Fractional B/W (%)	20 (25)	10 (14.6)	6.66 (6.66)
HPBW	123° (109°)	62° (53°)	-
Radiation efficiency (%)	98.2	97.7	97.6
Dual band	No	Yes	No

Tab. 1. Result comparison of both antenna designs with metamaterial antenna designed in [18] for 30 GHz. All measured values are mentioned in the brackets.



Fig. 6. E-field plot of patch antenna with IDC at 30 GHz frequency.

flows through the fingers of IDC. So we can conclude that the surface current flowing through patch gets confined within an IDC structure which results in more directive radiation pattern. This can also be verified from the values of HPBW of both the antennas mentioned in Tab. 1. The HPBW of patch antenna with IDC structure is much lesser than the normal patch. Similarly, insertion of IDC is responsible for generation of stronger fringing fields through the fingers as shown in Fig. 6. It can be observed from Fig. 6 that the intensity of field generated due to fingers is much higher than the rest of the patch. This in response increases flux density in that region and makes energy radiated by an antenna more concentrated which results in the enhancement of peak gain.

Similarly, we can observe that the radiation efficiency of the patch antenna with IDC is slightly reduced than that of the patch without IDC. The slight reduction in radiation efficiency is mainly due to the losses induced due to high intensity currents flowing through the fingers. This can also be observed in Fig. 3(d) that the intensity of the current flowing through the fingers is higher in comparison to the current flowing throughout the patch. This finger current increases the leakage current through the substrate of an antenna. Similarly, from a comparison of IDC loaded patch antenna with metamaterial antenna mentioned in [18], we can observe that in most of the characteristics, the proposed antenna outperformed the performance of antenna mentioned in the literature.

## 5. Array Analysis

In millimeter wave applications, use of single antenna is impractical as small wavelength results in the smaller range for communication. Hence most of the applications will need an array of an antenna where mutual coupling will play a vital role in overall array performance. To understand the impact of capacitive structure on mutual coupling, a two element linear array has been formed on Rogers RT duroid 5880 substrate using patch antenna with and without IDC as shown in Fig. 7(a) and Fig. 7(c). Figures 7(b) and (d) show fabricated linear antenna arrays. For the analysis distance between the patch elements of an array is kept as  $\lambda_0/4$  for both the cases. Simulated and measured mutual coupling results in both the arrays are











Fig. 7. (a) Designed two element linear array of patch antenna without IDC. (b) Fabricated two element linear array of patch antenna without IDC. (c) Designed array with IDC structure. (d) Fabricated array with IDC structure. (e) Measured and simulated mutual coupling between antenna array with and without IDC structure.

shown in Fig. 7(e). Mutual coupling in patch array without IDC comes out to be -17 dB. However, for a good isolated antenna array, the acceptable value for mutual coupling

should be around -16 dB. So mutual coupling of -17 dB is marginally better than the standard value. In patch antenna array with IDC, mutual coupling is improved from -17 dB to -25 dB. This value is acceptable according to isolation terms. This improvement in mutual coupling between the elements of an array is because of inserted IDC structure, which permits more number of radiating elements on the same substrate. The variations in measured and simulated results are due to the errors introduced while fabrication, soldering and measurement.

## 6. Conclusion

In this paper, an approach was proposed for enhancing the overall performance of an antenna by loading IDC structure on it. After insertion of IDC, better impedance matching was observed which was also verified from the reflection coefficient graph. It also resulted in the reduction of patch dimensions by around 10% along with the conversion of a wideband antenna to narrowband. This approach had also provided an additional resonance with an advantage of fine tuning as we had control over both the resonating frequencies independently. Insertion of capacitive structure helped in giving directionality to an antenna, hence for applications requiring a high directive antenna, this can be beneficial. Similarly, array analysis verified that the IDC patch resulted in the lower value of mutual coupling. Thus we can clearly state that the insertion of capacitive structure like IDC was responsible for the reduction of patch dimensions along with providing higher gain and multiband characteristics.

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