Novel 60 GHz CPW Array Antennas with Beam-Forming Features for Indoor Wireless over Fiber Networks

Ioannis Petropoulos[a], Spiros Mikroulis*[a], Adonis Bogris[b], Hercules Simos[c], Kostantinos Voudouris[a]

[a]Department of Electronics, Division of Telecommunications, Technological Educational Institute of Athens, Egaleo, 12210, Athens, Greece
[b]Department of Informatics, Technological Educational Institute of Athens, Egaleo, 12210, Athens, Greece
[c]Department of Electronics, Technological Educational Institute of Pireas, Pireas, 12210, Athens, Greece

ABSTRACT

In this study two types of coplanar waveguide (CPW) array antennas are designed and analyzed for use in a 60GHz Radio over Fiber indoor network. The first one is based on high permittivity Rogers 6010 and Indium Phosphide (InP) substrates incorporating slots as radiating elements. The second one utilizes stacked geometry based on the above substrates. Both arrays present more 1 GHz bandwidth and 10dBi gain. Furthermore they can provide beam-forming operation by properly adjusting the signal's amplitude and phase. A Least Mean Square (LMS) algorithm is generated for this purpose and the radiation pattern is steered accordingly. At last, a photodiode is simulated using equivalent circuit and is adopted with the proposed arrays, and an optical beam forming scenario is discussed.

Keywords: CPW array antennas, optical beam-forming, Radio over fiber

1. INTRODUCTION

In recent years, ultra-broadband 60GHz wireless short area indoor networks have attracted much attention. Ongoing this, several wireless standards have already been proposed to benefit from the 60GHz unlicensed band, an example is wireless high definition audio/video standard (Wireless HD) which is based upon IEEE 802.15.3c. However, 60 GHz spectrum imposes several challenges in a real environment due to the increased path loss and reduced coverage, which envisages a high density of installed radio access points in contrast to social needs for energy conservation and cost reduction. In this case, Radio (Wireless) over Fiber (RoF) technology combines a low cost implementation, due the simplification of Base Stations (BSs) to Remote Antenna Units (RAUs) transferring thus all the processing and modulating equipment to a central station (CO), with a green radio approach, due to the reduction of the overall consumed power.

A key point for further development of this technology is the low cost implementation of an optical-wireless transceiver. By proper adaptation/matching of wireless, optical and microwave transceiver components, monolithically or hybrid, integrated, radio over fiber technology will benefit in terms of low-cost, ultra compactness, and improved link budget/network coverage. In this case, a planar antenna is a promising candidate due to its low-cost, lightweight, simple manufacture and compatibility with MMIC/OEIC technology. In addition to this, a planar antenna can be fabricated in an array configuration, increasing the achievable gain, and enabling mm-wave techniques in the optical domain to utilized for beamforming in smart antenna applications. However, antennas directly integrated on MMIC/OEIC materials are performance limited due to the high dielectric constant substrates.

*corresponding author, e-mail: spirosm@teiath.gr (S. Mikroulis)

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In this work, various antenna designs on high permittivity material are compared, for application in a beam-switched 60GHz wireless over fiber based indoor system, and evaluated with respect to gain, bandwidth, and beam forming features, highlighting the needs for selecting MMIC/OEIC matched dielectric substrate and coplanar configuration in order to demonstrate an efficient integrated adaptive planar array antenna for a contribution to the simple and low-cost deployment of the photonic-wireless transceiver.

2. DESIGN OF CPW SLOT LINEAR ARRAY ANTENNAS

Two kinds of slot antennas are modeled using various high dielectric permittivity substrates for integration with optoelectronic (O/E) devices (i.e. photodiodes, Mach Zehnder modulators, and mm-wave amplifiers). The first kind of slot antenna utilizes Rogers 6010 substrate with ε_r=10.2 and thickness h=0.254mm while the second one incorporates InP substrate with ε_r=12.4 and thickness h=0.35mm. Both slot antennas were designed in HFSSv11 and optimized to achieve desired characteristics in terms of resonant frequency. Coplanar waveguide structure (CPW) has been utilized as it provides low losses for the frequency of interest (60GHz), as well as compatibility with O/E devices [1-3]. The dimensions of the CPW structure have been calculated using the formulas defined in [4]. In Fig. 1 the cross section of a CPW structure is drawn. Dimensions s, w and h are introduced in the formulas that follow to calculate the effective permittivity (ε_{eff}) and the characteristic impedance (Z_0) of the transmission line.

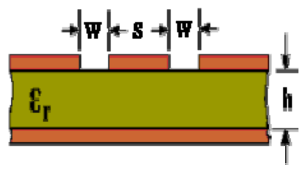


Figure 1. CPW structure

$$k = \frac{S}{S+2W} \quad (1a)$$

$$n = \frac{\tanh(\frac{\pi S}{4h})}{\tanh[\frac{\pi(S+2W)}{4h}]} \quad (1c)$$

$$m = \sqrt{1-k^2} \quad (1b)$$

$$p = \sqrt{1-n^2} \quad (1d)$$

$$\varepsilon_{eff} = \frac{1+\varepsilon_r(\frac{m}{k})(\frac{n}{p})}{1+(\frac{m}{k})(\frac{n}{p})} \quad (1e)$$

$$Z_0 = \frac{60\pi}{\sqrt{\varepsilon_{eff}}} \frac{1}{\frac{k}{m}+\frac{n}{p}} \quad (1f)$$

The proposed antennas have similar design and can be seen in Fig. 2.

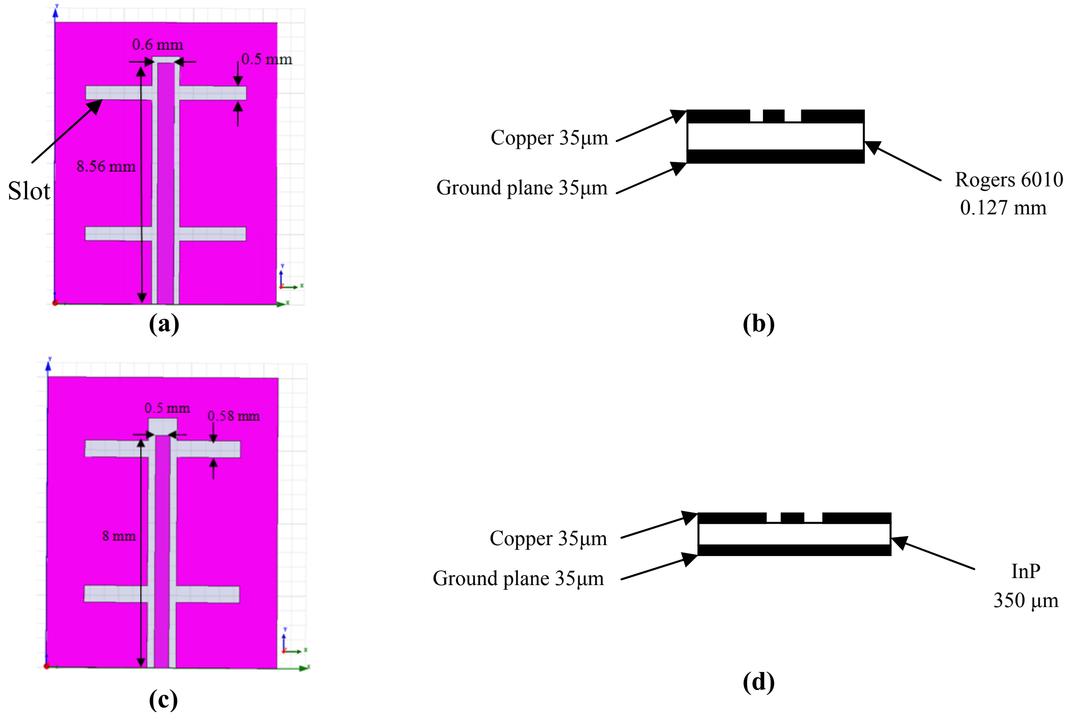


Figure 2. Antenna designs; (a) Slot antenna with Rogers 6010 substrate (b) Cross section (c) Slot antenna with InP substrate (d) Cross section

The denoted slot (Fig. 2a) performs as the radiating element. The slot length is equal to $\lambda_0/2$ where λ_0 is the wavelength in free space according to the specified carrier frequency. Slot width is a small fraction of wavelength [5]. The above designs have been integrated into two linear arrays, for each substrate, in order to produce a radiation system for indoor coverage in 60GHz compliant with the specifications of the IEEE802.15.3c standard.

The slot dimensions have been properly adjusted to attain resonance at 60GHz. Furthermore the distance between slots is carefully defined to produce low side lobe levels and prevent grating lobes [6]. Fig. 3 shows the proposed arrays, with Rogers 6010 and InP substrate. Also the distance between the slots is denoted.

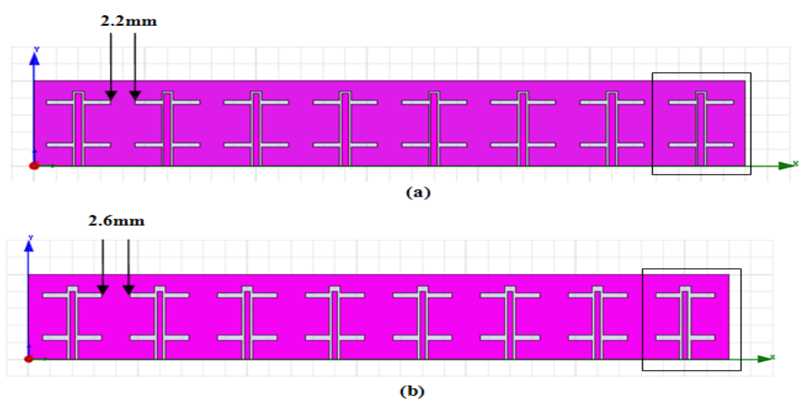


Figure 3. CPW Linear array; (a) with Rogers 6010 substrate (b) with InP substrate

Both linear arrays have dimensions x=64mm and y=10mm. The S_{11} parameter of the elements denoted in the black brackets of Figures 3a and 3b is drawn below:

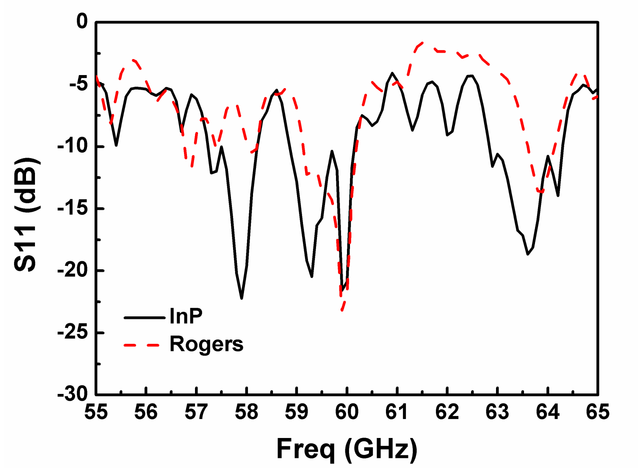


Figure 4. S_{11} as a function of frequency

Rogers 6010 linear array has three resonant frequencies: in 59.9GHz (-23.19dB), in 56.9GHz (-11.77dB) and in 63.9GHz (-13.66dB). Bandwidth is estimated to be 1.1GHz. The InP linear array has four resonant frequencies: in 57.9GHz (-22.21dB), in 59.3GHz (-20.47dB), in 59.9GHz (-21.57dB) and in 63.6GHz (-18.66dB). Bandwidth in this case is 1.32GHz.

The Radiation patterns of the proposed CPW linear arrays with Rogers 6010 and InP substrates for 59.9GHz are depicted in Figs 5a and 5b, respectively.

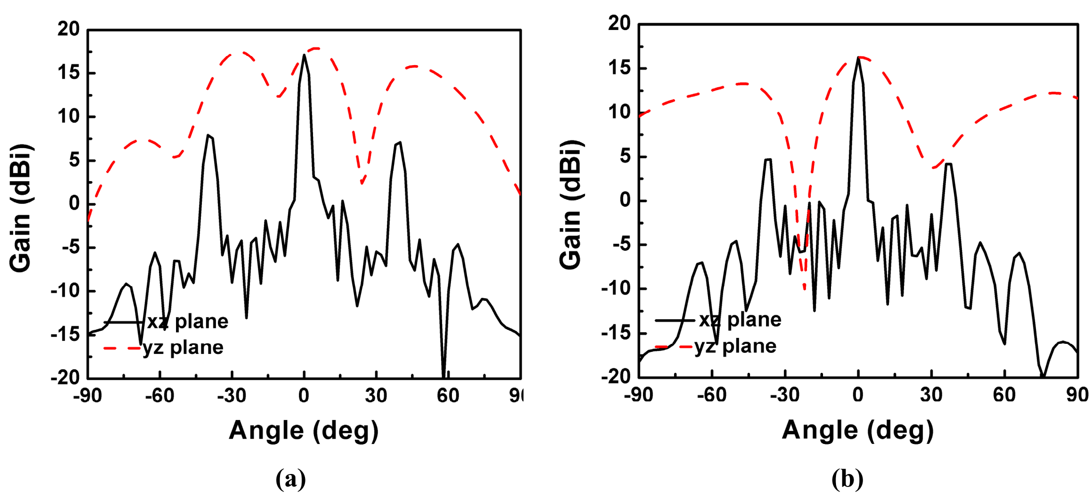


Figure 5. Radiation pattern of the CPW linear array; (a) with Rogers 6010 substrate (b) with InP substrate

The linear array based on Rogers 6010 substrate provides 17.15dBi and 17.88dBi in xz and yz planes respectively while the InP linear antenna provides 16.25dBi gain in both planes. Gain appears to be reduced in the case of InP due to the higher dielectric permittivity of InP substrate which actually leads to the presence of multiple TM modes in the frequency region of 60GHz.

The features of both CPW linear arrays are denoted in table 1.

Antenna	S_{11} (dB)	Bandwidth (GHz)	Gain (dBi)	HPBW (deg)	
				xz plane	yz plane
Rogers 6010 array	-23.19 (59.9GHz)	1.1	17.88	3.8	19.33
InP array	-21.57 (59.9GHz)	1.32	16.25	4	23.84

Table 1. CPW slot linear arrays features

Bandwidth has been estimated for S_{11}<-10dB. For the application of indoor use in 60GHz, bandwidth has to be as large as possible (typically >1 GHz) but the utilization of high permittivity substrates limits the desired high frequency characteristics.

3. DESIGN OF STACKED CPW LINEAR ARRAY ANTENNAS

In order to further improve the desired bandwidth characteristics limited by the high permittivity two types of 1×8 CPW linear arrays are designed incorporating stacked geometry for bandwidth enhancement [7]. In this case two types of substrates are investigated: The first one utilizes Rogers 6010 substrate and the second one InP substrate. The proposed stacked geometry can be seen in Fig. 6.

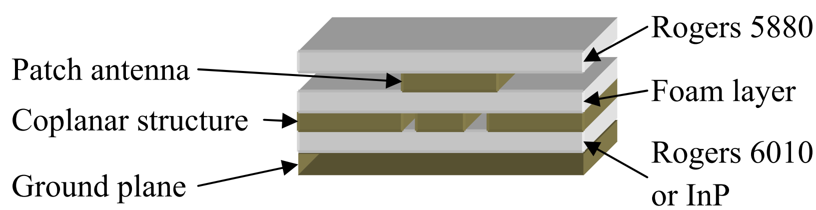
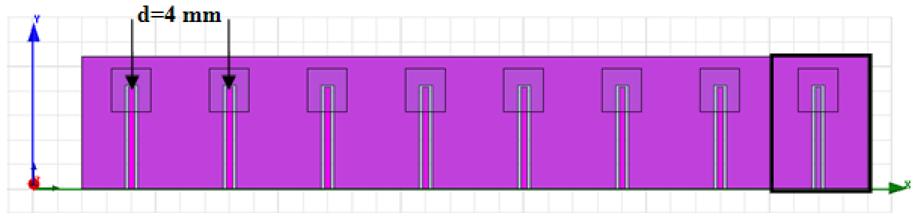
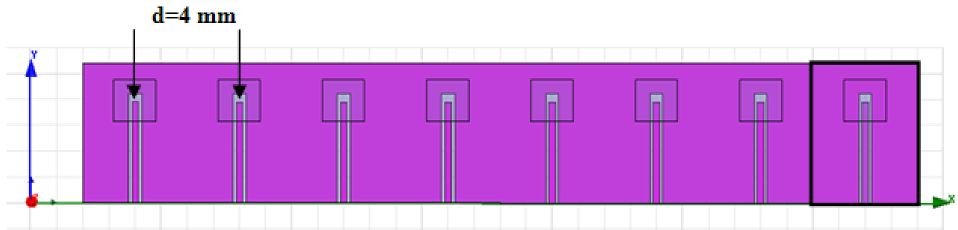


Figure 6. Stacked geometry

The Rogers 6010 stacked linear array can be seen in Fig. 7a, where a Copper ground plane with a thickness of 35μm is utilized on a Rogers 6010 (ε_r=10.2, h=0.127mm) substrate. A foam layer (ε_r=1) with thickness h=0.15mm is also incorporated. On top of the radiating element, a Rogers 5880 (ε_r=2.2, h=0.127mm) layer is utilized for producing a compact structure and protecting the patch antenna from spoilage. Dimensions of the patch elements are x=1.6mm and y=1.75mm. In fig. 7b a second stacked linear array is presented incorporating the same structure but instead of Rogers 6010, InP (ε_r=12.4, h=0.35mm) is used. In this case the dimensions of patches are adjusted for achieving resonance in the desired frequency range. The dimensions of the patches are x=y=1.6mm. In both cases, the inter-element spacing is d=0.8λ_0. This value has been chosen for maintaining low side lobe levels and gain enhancement [8].



(a)



(b)

Figure 7: Stacked Linear array; (a) with Rogers 6010 (b) with InP

At the following diagram the S_{11} parameter is depicted as a function of frequency showing the operation performance of the designed arrays. The curves correspond to the elements in black frames are depicted in figure 7a and 7b, respectively.

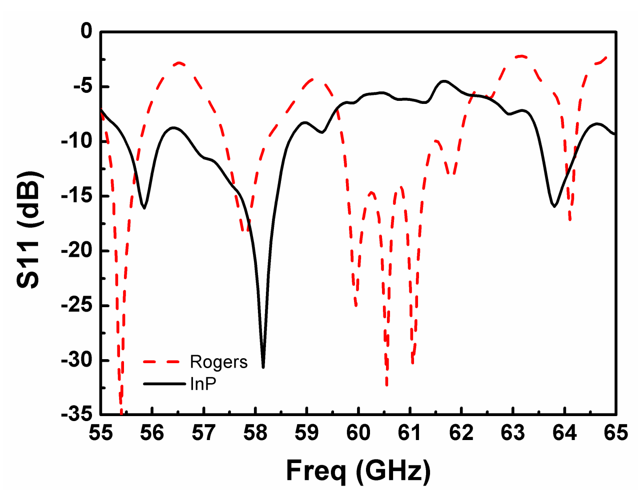
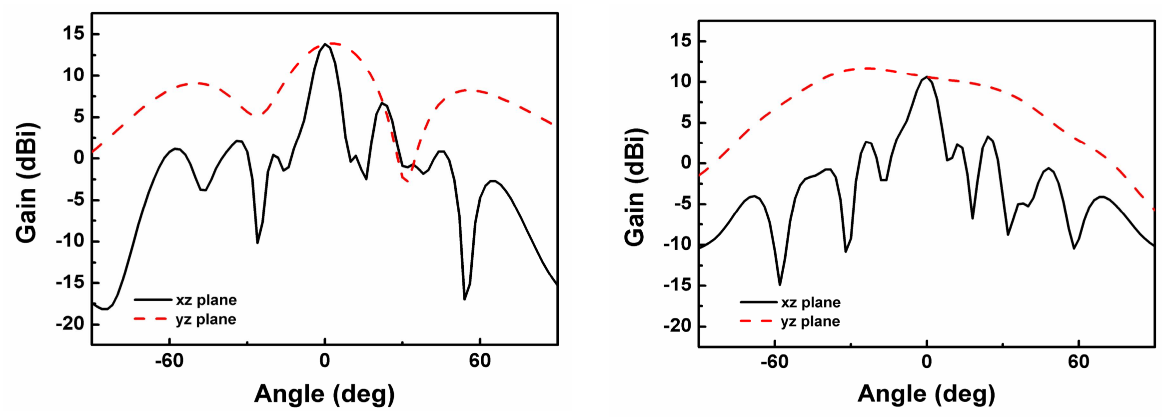


Figure 8: S_{11} regarding frequency

Rogers 6010 stacked linear array has three resonant frequencies: in 59.95GHz (-25dB), in 60.55GHz (-32.27dB) and in 61.05GHz (-30.43dB). Bandwidth is calculated to be 1.82GHz. The InP linear array has three resonant frequencies: in 55.85GHz (-16.07dB), in 58.15GHz (-30.62dB), in 63.8GHz (-15.93dB). In this case bandwidth is calculated to be 1.93GHz.
The radiation pattern of the stacked linear arrays is shown in the figure below.



(a) **(b)**

Figure 9: Radiation pattern; (a) Stacked linear array with Rogers 6010 (b) Stacked linear array with InP

The stacked linear array based on Rogers 6010 substrate provides 13.82dBi gain in xz plane and 13.91dBi in yz plane. The aforementioned Radiation pattern has been derived for the 60GHz frequency. In the case of InP substrate, the gain is estimated 10.61dBi in xz plane and 11.68dBi in yz plane for the frequency of 58GHz. The features of the aforementioned arrays are included in the following table.

Antenna	**S_{11} (dB)**	**Bandwidth (GHz)**	**Gain (dBi)**	**HPBW (deg)**	
				xz plane	**yz plane**
Rogers 6010 array	-25 (59.95GHz) -32.27 (60.55GHz) -30.43 (61.05GHz)	1.82	13.82	8.4	28
InP array	-16.07 (55.85GHz) -30.62 (58.15GHz) -15.63 (63.8GHz)	1.93	10.61	9.5	81.63

Table 2: Stacked CPW linear array features

The presented arrays provide an improved bandwidth as a result of the utilized stacked geometry. The combination of a high permittivity substrate (Rogers 6010 or InP) with foam layer and Rogers 5880 substrate, produces a structure of average total permittivity which is:

$$\varepsilon_{av} = \frac{\varepsilon_r h_{d1} + \varepsilon_r h_a + \varepsilon_r h_{d2}}{\frac{h_t}{3}} \tag{2a}$$

where ε_r is the permittivity of the Rogers 6010/InP substrate,
h_{d1} is the thickness of the Rogers 6010/InP substrate,
h_a is the thickness of the foam layer,

h_{d2} is the thickness of the Rogers 5880 substrate and
h_t is the total thickness of the stacked structure

The average dielectric constant causes bandwidth enhancement [6] according to the formula:

$$BW \approx \frac{1}{\sqrt{\varepsilon_{av}}} \tag{2b}$$

Furthermore the bandwidth in the case of InP is slightly increased as a result of higher permittivity. The increased bandwidth leads to lower quality factor which limits the efficiency of the antenna. Thus, the gain is appeared reduced in this case. Both arrays produce low HPBW and can be used for point to point communication.

4. POTENTIAL LINEAR ARRAY OPTICAL BEAM-FORMING APPLICATIONS

The aforementioned arrays can provide beam-steering properties if properly connected with a electrical circuit to adjust accordingly the phase and the amplitude of the excitation signals. In the case of a Radio over Fiber network optical beam-forming can be realized with the utilization of True Time Delay units as depicted in Fig. 10:

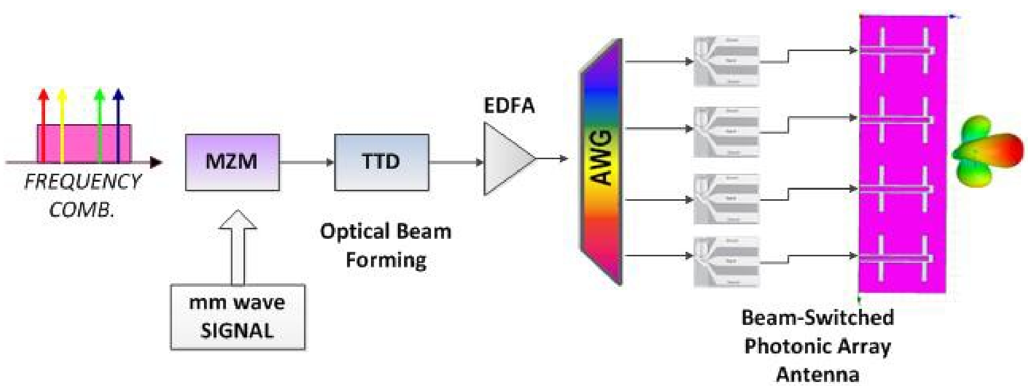


Figure 10: Optical beam-forming setup

In this case a frequency comb produced by a multiwavelength WDM source is directly feeding a Mach Zehnder modulator on which a 30 GHz signal is applied for a square law frequency (i.e. at 60GHz) up conversion at the photodiode, using a typical double side band suppressed carrier (DSB-SC) scheme. In the next step an optical true time delay (TTD) scheme is configured using a dispersive optical medium as an optical fiber or integrated version using ring resonators in a cascaded configuration. After optical amplification and wavelength demultiplexing the proposed photonic array antenna can be implemented based on either a hybrid integration scheme using coplanar high speed photodiodes bond wired to the designed Rogers Duroid 6010 array antenna either on a monolithically InP platform. Additionally, the proposed linear arrays should be equipped with beam-forming capabilities in order to be compliant with the IEEE802.15.3c protocol for indoor use in 60GHz as described in [9]. There are several beam-forming algorithms presented in literature such as the Constant Modulus Algorithm (CMA) [10], the Recursive Least Square (RLS) [11] and the Least Mean Square algorithm (LMS) [12]. These algorithms are based on an iterative process where a weight equation is updated to produce an optimal radiation pattern according to the specified criteria. In this study, the LMS algorithm is applied because of its simplicity, low convergence time and ease of computation.

In general, for a linear array of N elements, the problem of radiation pattern shaping can be expressed through the equation [13]:

$$R(\theta) = w^{H}(n)S(\theta) \tag{3}$$

where R(θ) is the array response, w(n) is the weight vector and n denotes the radiation element.

The superscript "H" denotes the transpose conjugate and S(θ) is the steering vector equal to : $S(\theta) = \left[1, e^{-j\theta}, e^{-j2\theta}, ..., e^{-j(N-1)\theta}\right]^T$. The superscript "T" denotes the transpose matrix.

Figure 11 represents the case of a linear array of N elements. The angle "θ" is the angle of incidence with respect to the tangential to the array level. The radiation elements are positioned in equal distance.

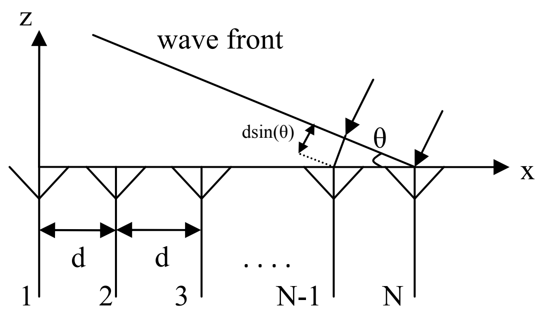


Figure 11: Linear array with equidistantly positioned elements

The LMS algorithm calculates the weight function w(n) iteratively until it reaches as close as possible to a reference signal. The weight update is performed according to the equation [14]:

$$w(n+1) = w(n) + \mu x(n)[d^{*}(n) - x^{H}(n)w(n)] \tag{4}$$

where x(n) is the array input, d(n) is the reference signal and μ denotes the rate of adaptation.

The algorithm through iterations evaluates the w(n) vector for minimizing the expression $d^{*}(n) - x^{H}(n)w(n)$.

The arrays presented in sections 2 and 3 can be used in applications where beam-forming is required to produce a radiation pattern with desired characteristics. This can be achieved by properly adjusting the phase and amplitude of the excitation signal that feeds each port of the arrays. LMS algorithm was generated in Matlab to produce the required amplitude and phase in order to produce a pattern based on requirements. A scenario was considered demanding maximums at angles $\theta=18^0$ and $\theta=-18^0$. LMS was generated and the results in terms of amplitude and phase are denoted in the table below:

Excitation current	El.1	El. 2	El. 3	El. 4	El.5	El. 6	El. 7	El.8
Amplitude (V)	1	1.2	1.027	1.13	1.13	1.023	1.2	1
Phase (deg)	0	180.7	6	176.7	7	178	2	184.11

Table 3: Fig. 9: Radiation pattern with three maximums at $\theta=-18^0$ and $\theta=-18^0$.

The above values were entered in each port of the Rogers 6010 CPW slot array presented in section 2 and the pattern was steered accordingly as can be seen below:

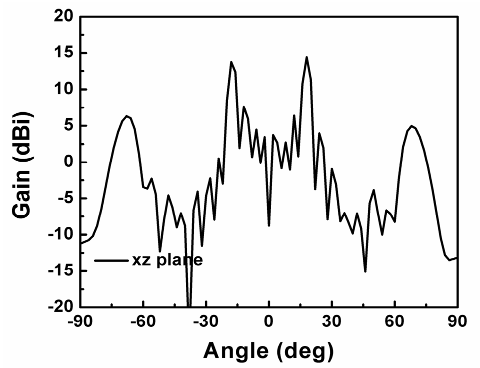


Figure 12: Radiation pattern with two maximums at θ=18⁰ and θ=-18⁰.

5.PHOTODIODE DESIGN

The slot CPW linear array and the stacked CPW linear array based on Rogers 6010 substrate, presented in sections 2 and 3 respectively, can be connected via bond-wires with a photodiode [15] to provide an efficient hybrid integrated optoelectronic device. The equivalent RLC circuit of the photodiode plus the bond-wires was designed in ADS2009 and can be seen in figure 13.

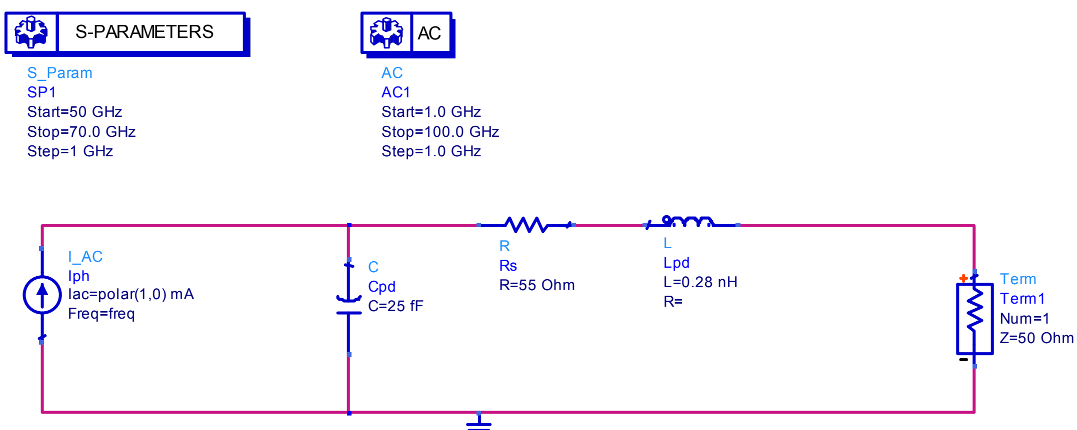


Figure 13: RLC circuit of photodiode plus bond-wires

The photodiode is represented by a current source with a capacitor and a resistance. Bond-wires are denoted by a series inductance. The capacitor and the inductance for the 60GHz resonant frequency are defined by the following equations [16]:

$$C_{pd} = \frac{\varepsilon_0 \varepsilon_r A}{d_{pn}} + C_{st} \tag{5}$$

$$L_{pd} = \frac{\mu_0}{2\pi} L(\ln(2\frac{L}{r} - \frac{3}{4}) \quad (6)$$

where ε_r is the dielectric constant of InGaAs material,
A is the depleted region,
C_{st} is a parasitic capacitance,
d_{pn} is the thickness of the depleted region,
L is the length and r the radius of the bond-wire,
ε_0 and μ_0 are the permittivity and the permeability of free space respectively

The S_{11} of the photodiode plus the bond-wires is depicted in figure 14.

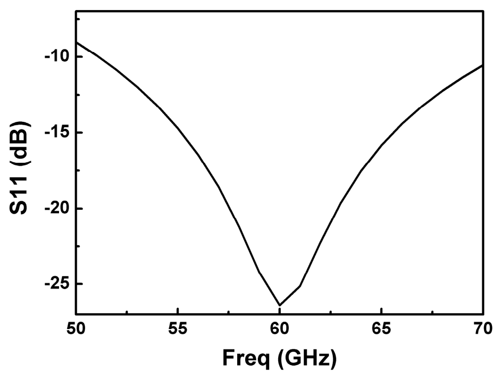


Figure 14: S_{11} of the photodiode plus bond-wires

A resonance is presented for 60GHz (S_{11}=-26.393dB) and bandwidth is approximately 20GHz. Photodiode plus bond-wires can be combined with the Rogers 6010 based stacked and slot arrays in a Radio over Fiber network.

6. CONCLUSIONS

In this study, two CPW slot array antennas were designed and presented to be used in an indoor environment under a Radio over Fiber network. These arrays are compliant with the IEEE 802.15.3c standard regarding their radiation characteristics, providing resonant frequency in the 60GHz band. The CPW slot array antennas are based on high permittivity substrates Rogers 6010 and Indium Phosphide (InP) for integration with opto-electronic devices. The Rogers 6010 CPW slot array presents 17.88dBi gain with 1.1GHz bandwidth while the InP CPW slot array provides 16.25dBi gain and 1.32GHz bandwidth. Furthermore two stacked CPW array antennas were designed based on the previously mentioned substrates. In this case the stacked geometry is utilized for bandwidth enhancement in the 60GHz frequency band. The Rogers 6010 stacked CPW array, provides 13.82dBi gain with 1.82GHz bandwidth while the InP stacked CPW array presents 10.61dBi gain and 1.93GHz bandwidth. The stacked geometry indeed leads to bandwidth increase but the incorporation of multiple substrates creates surface waves and limits the antenna efficiency and gain.
In addition a reference regarding optical beam-forming is denoted and a scenario of beam-steering is presented based on Least Mean Square (LMS) algorithm. The amplitude and phase of the excitation currents were calculated and introduced in the Rogers 6010 CPW slot array shaping the radiation pattern accordingly.

Moreover a photodiode design was presented for the proper optical demodulation. The photodiode is expected to be connected with the Rogers 6010 CPW slot and stacked arrays via bond-wires. The S11 parameter of the photadiode plus the bond-wires was presented providing resonance at 60GHz and bandwidth equal to approximately 20GHz.
The presented arrays provide features compatible with the IEEE802.15.3c standard specifications in terms of beam-forming capability, bandwidth, gain and can be major candidates for indoor use in 60GHz frequency band in a Radio ovfer Fiber network.

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