Efficient Design Methodology for Optically Controlled Adaptive Antenna Arrays

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***Abstract*—This paper proposes an efficient design methodology for developing optical controlled adaptive antenna arrays. It is based on the use of circuital and full wave electromagnetic solvers in conjunction with an optical numerical tool. In order to illustrate to proposed methodology, it is presented the development of an optical delay line for an antenna array based four patch antennas operating at 5.8 GHz. The array has been numerically evaluated using a 50 km Radio over Fiber (RoF) system, responsible to transmit the RF signal from the Central Office to the Remote Antenna Site. It has been used the following pieces of software: VPI Transmission Maker for optical domain simulations; Designer and HFSS from ANSYS for electrical domain simulations. The last two are easily integrated, since the same company had produced them. On the other hand, it was necessary to create an interface for enabling the integration between VPI Transmission Maker and them.**

***Index Terms*— Adaptive antennas arrays, Beam steering, Optical delay line and Radio over Fiber.**

I. INTRODUCTION

Adaptive antennas can manipulate the radiated beam by controlling the phase of radiating elements, not requiring a physical movement of the structure [1]. For a given radiation direction, the phase between adjacent antennas must be determined and provided by a feeding network. Conventionally, this is done in the electrical domain by using microstrip technology, associated or not with PIN diodes [2]. However, these structures have limited bandwidth and high insertion loss, size, weight, and electromagnetic interference with the antennas [2]. With optical delay lines these limitations are overcome with the features of low attenuation, weight and high bandwidth of optical fibers [3]-[5]. In broadband systems, electrical phase shifters produce a deviation on the radiated main lobe due to its frequency sensitivity. This shift in the main lobe with frequency is known as *beam squint* [5][6]. Optical delay lines are used to mitigate this effect, allowing broadband operation.

The proposed optical delay line is based on four Single Mode Fibers (SMFs) with different lengths. The RF signal is equally divided and transmitted by using Radio over Fiber (RoF) technology, leading to different accumulated dispersions and, consequently, different time delays. Beam steering is ensured by using a tunable laser source, as shown in Fig. 2. The optical delay line was validated by using a linear uniform antenna array based on four patch antennas operating at 5.8 GHz.

This paper is organized as follows. Section II describes details on the integration of VPI, Designer and HFSS. The design procedure of the proposed optical delay line is presented in Section III. Section IV is dedicated to the antenna array design and validation in HFSS. Numerical results on the optical delay line performance are presented in Section V, by means of a comparison between a theoretical delay and an optical delay. Conclusions and future works are treated in Section VI.

II. SOFTWARE INTEGRATION

The simulation cycle for integrating pieces of software on optical and electromagnetic domains is illustrated in Fig. 1, where the continuous arrow represents optical domain and dashed arrow represents the electrical domain. In VPI, it is generated the information signal that is transported through RoF system in order to feed the antenna array, i.e. RoF system and optical delay line design. Designer is used to provide the feeding signals from VPI to the antenna array in HFSS. Briefly, the antenna array feeding signals are generated in VPI and used as voltage supplies in Designer, which are applied to the antennas present in HFSS. By applying this approach, it is possible to perform the interaction between optical and electromagnetic domains (VPI and HFSS), having Designer as a bridge. Therefore, as antenna array radiation pattern and field distributions can be analyzed in accordance to the optically generated feeding signal.

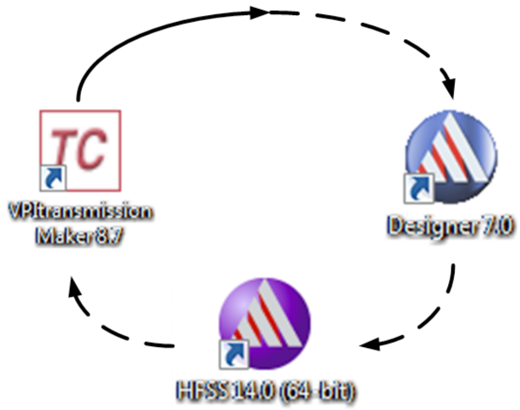


Fig. 1. Simulation cycle for software integration.

A. *VPI Transmission Maker*

Initially, it is implemented a 50 km RoF link operating at 5.8 GHz, representing a remote generation of the feeding signals, by using VPI. The complete optical system diagram implemented in VPI is shown in Fig. 2. The RF signal is applied to an amplitude external modulator with a tunable laser. This optical signal propagates through a 50 km SMF link with booster and line amplification to compensate attenuation and insertion loss components. On remote antenna site there is an optical splitter, which equally divides the optical signal into four SMF paths to provide different delays. These delayed signals are then applied to PIN photodetectors, filtered and amplified to compensate receiver loss. The VPI electrical signal extraction is performed by a time sampling procedure and the exported data is composed by amplitude and equivalent time. This exported data is used as a voltage supply in Designer to excite the HFSS antenna array.

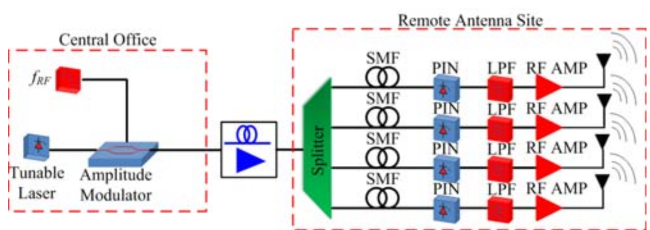


Fig. 2. Optical system diagram implemented in VPI.

B. *Designer*

Designer performs a bridge between VPI and HFSS for the interaction between optical and electrical domains. It can generate a voltage or current source whose waveform is governed by an external file, with amplitude and equivalent time information. With VPI exported data an excitation source can be used at any built circuit in Designer. Designer and HFSS integration is simply and directly, since the same company had produced them. It is created in Designer a component representing HFSS antenna array, where its terminals indicate the antenna array input ports. Thus, these terminals are connected at voltage sources containing the delayed signals from VPI.

C. *HFSS*

HFSS is an electromagnetic simulator of 3-D arbitrary structures that has scattering matrix (S-parameters, Y and Z), 2-D and 3-D electromagnetic fields (near and far fields) as main output parameters, and any other parameter obtained with combination or manipulation of them. By using HFSS, it is possible to analyze the beam steering due to the optical delay signals generated in VPI. The antenna array simulated in HFSS is presented in Fig. 3.

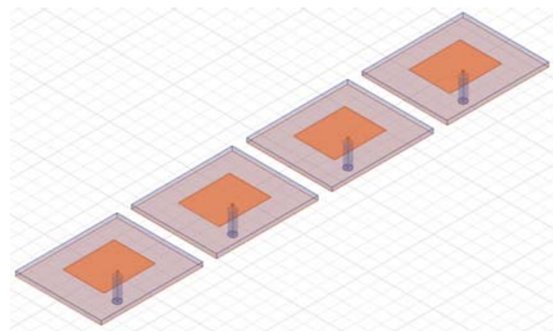


Fig. 3. HFSS model of adaptive antenna array.

III. Optical Delay Line

Conventional electrical phase control of phased array suffers from the narrow RF bandwidth limitation, causing frequency dependent beam shape known as beam squint. Fig. 4 illustrates radiated beam deviation as a function of frequency, taking f_c as a reference. This problem is overcome by replacing the phase delays with True Time Delays (TTD) lines, which are done by optical means [5].

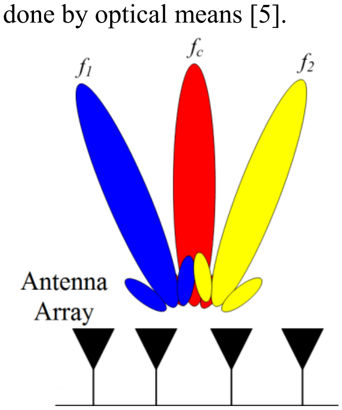


Fig. 4. Beam squint phenomenon.

Besides squint free, optical delay lines have other advantages, such as electromagnetic interference (EMI) immunity, low loss, small size, reduced weight, easy integration into optical systems as RoF, among others. Therefore, optical delay lines provide wideband operation with low loss, size and complexity compared to electrical phase shifter feeding networks.

Optical delay lines can be constructed using many strategies: free space optics [7], switching between different fibers length [3][4], dispersive optical medium with tunable lasers [3], nonlinear effects present in materials such as lithium niobate (LiNbO3) [8] and piezoelectric crystals (PZT) [7], fiber Bragg grating (FBG) with tunable lasers [9], and so forth. Our optically controlled antenna array is based on a dispersive optical medium to generate different delays by changing the laser wavelength.

A. Proposed optical delay line

A change in the beam direction of θ requires a phase shift of $\Delta\phi$. In a electrical phase shifter its is given by [10]:

$$\Delta\phi = 2\pi\frac{\Delta L}{\lambda} = 2\pi\frac{d\sin\theta}{\lambda} \quad (1)$$

where d is the antenna element spacing and λ is the operating wavelength. In a broadband operation, each frequency will produce a slightly different angle θ, broadening the radiated beam.

Replacing electrical phase shifter by optical delay lines, the required adjacent element delay is [9]:

$$\Delta\tau = \frac{d\sin\theta}{c} \quad (2)$$

where c is electromagnetic wave velocity. As we can see, with TTD the beam pointing direction is frequency independent.

Our optical delay line is based on SMF as a dispersive optical medium. It was been considered a chromatic dispersion of 16 ps/nm/km at 1550nm and a dispersion slope of 0.092 $ps/nm^2/km$. For a specific wavelength, the accumulated dispersion is the product of dispersion (ps/nm/km) by distance in kilometers. We have chosen four different fiber lengths that provide the required delay by taking into account the wavelength of the tunable laser and fiber dispersion properties. The optical delay lines are based on SMFs with the following lengths: 1, 2, 3 and 4km. By using this setup is demonstrated a beam steering of an antenna array based four patch antennas from -20 to 20°.

B. Calculating optical delay line

The antenna array has an element space of 25.86 mm, thus the steering angle is given by:

$$\theta = \sin^{-1}\left(\frac{\Delta\tau}{86.20\times10^{-12}}\right) \quad (3)$$

A steering angle of -10° requires an advance of 14.97 ps between the adjacent elements; 20° needs a delay of 29.48ps, and so forth. According to the four different lengths SMFs and steering angle, tunable laser wavelength is chosen. With the proposed optical delay line is set an arbitrary steering angle and varied the RF frequency to prove the squint-free behavior. For a 90° steering angle the RF frequency is varied from 3GHz to 10GHz and the results plotted in Figure 5. As we can see, the optical delay line is frequency independent, allowing wideband operation.

Another way to compare phase shifter and optical delay line is through the array factor response [5][10]. For a frequency of 5.8 GHz, an element space of 25.86 mm, 4 elements and varying the frequency from 3.8 to 7.8GHz, the difference response of TTD and phase shifter is shown in Fig. 6.

IV. ADAPTIVE ANTENNA ARRAY

It was been designed an adaptive antenna array in order to validate the proposed technique and the use of optical delay lines. By feeding the array elements with different phase shifts, it is possible adapt its radiation pattern and radiate to different spatial regions [11]. This feature in conjunction with a RoF system, greatly simplifies the physical structure of the radio base station, which for this scenario presents only the radiator element and an integrated set containing the optical delay line, photodetection and the processing part of electrical signal. The centralization enables to remotely and efficiently control the array radiation pattern in the optical domain.

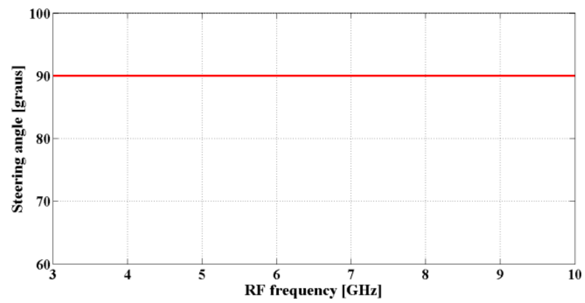
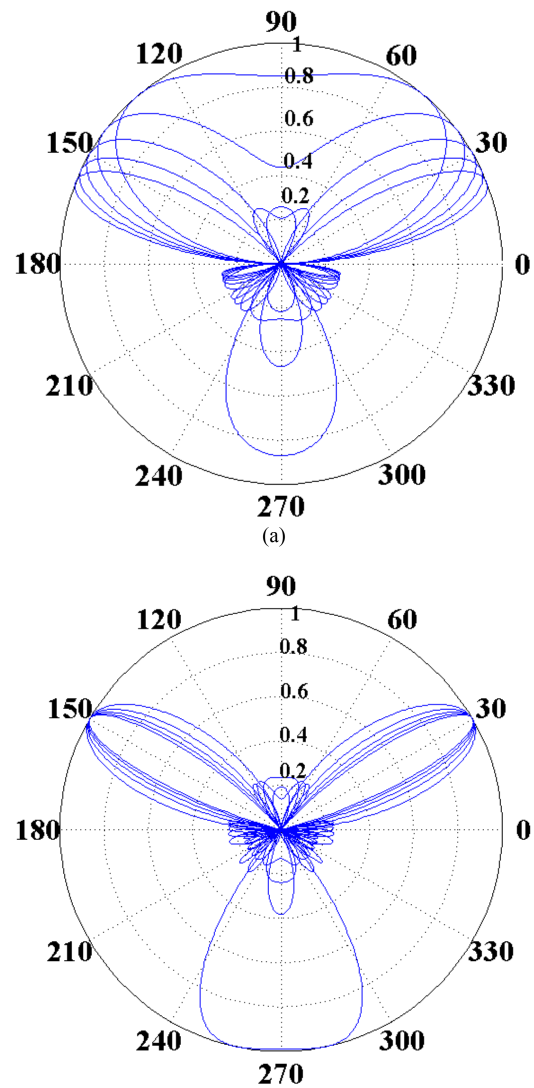


Fig. 5 Optical delay line behavior with RF frequency.



(b)
Fig. 6 Array factor of four linear and uniform array. (a) Phase shifter response. (b) Optical delay line response operating from 3.8 to 7.8 GHz.

A. Patch Antenna

Initially, a single patch antenna in a substrate with dielectric constant of $\varepsilon_r = 2.2$, 1.58 mm thickness and 0.038 mm thick conductor has been designed based on the methodology proposed in [12]. By using these variables, one can calculate an average dielectric constant, which is a parameter for determining the width of the antenna:

$$\varepsilon_{rea} = \frac{\varepsilon_r + 1}{2} \tag{2}$$

The antenna radiator element width is calculated by substituting (2) into (3).

$$b_c = \frac{3 \times 10^8}{2 f_0 \sqrt{\varepsilon_{rea}}} \tag{3}$$

where f_0 is the antenna operation center frequency.

To obtain the antenna length, first it is necessary to calculate the constants p and q that are empirical variables given by (4) and (5).

$$p = 1 + \frac{1}{49} \ln \left\{ \frac{\left(\frac{b_c}{h}\right)^4 + \left[\frac{b_c}{(52h)}\right]^2}{\left(\frac{b_c}{h}\right)^4 + 0.32} \right\} + \frac{1}{\sqrt[3]{6539}} \ln \left[1 + \frac{\left(\frac{b_c}{h}\right)^3}{5930} \right] \tag{4}$$

$$q = 0.563 \exp\left[\frac{-2}{(10\varepsilon_r + 3)}\right] \tag{5}$$

Applying (4) and (5) into (6) it was obtained the variable g.

$$g = \left(1 + \frac{10h}{b_c}\right)^{-pq} - \left(\frac{t \ln 4}{\pi \sqrt{h b_c}}\right) \tag{6}$$

where h is the substrate thickness and t is the conductor thickness. The effective dielectric constant used for the calculation of the total length is shown at (7).

$$\varepsilon_{ref} = \left(\frac{\varepsilon_r + 1}{2}\right)\left[1 + g\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\right] \tag{7}$$

where ε_r is the characteristic dielectric constant of the substrate that will be used to calculate the total length of the antenna (8).

$$L = \frac{3 \times 10^8}{2 f_0 \sqrt{\varepsilon_{ref}}} - 2\Delta L \tag{8}$$

where ΔL is the increase in the effective length [12].

B. Array simulation

After the calculations of one patch antenna, the array has been constructed using HFSS software, as shown in Figure 3. The spacing between the array elements is λ/2 to enable a proper bema steering [13].

The chosen parameter for determining the impedance matching was the return loss (S_{11}) less than -10dB, representing an irradiation of 90% of the energy delivered to the antenna. Fig. 7 shows the return loss the array.

Fig. 8 presents the frequency band ranging from 5.66 to 5.93 GHz with a dip of -19 dB at 5.8 GHz. At the center frequency, the antenna lobe assumes a radiation pattern with 14.5 dBi gain as shown in Figure 8 and 9, for all antennas in phase.

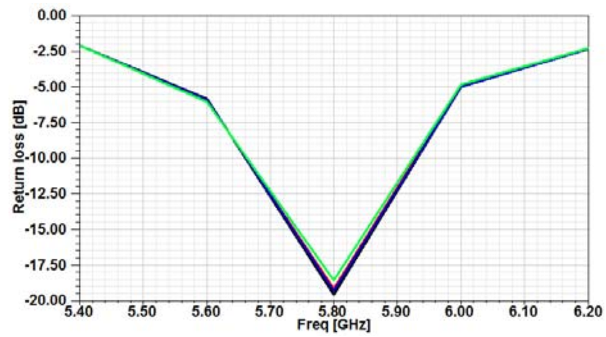


Fig. 7 Antenna array return loss.

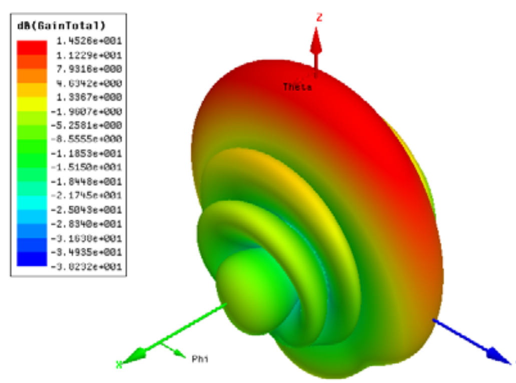


Fig. 8 3-D radiation pattern.

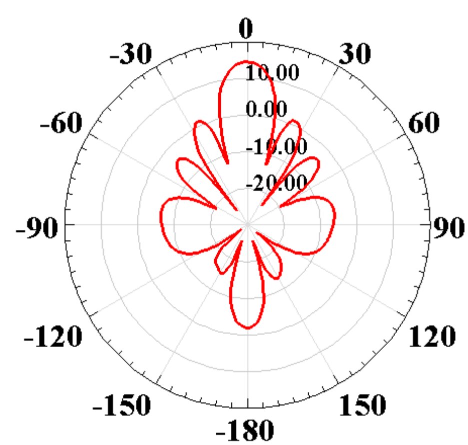


Fig. 9 Antenna array radiation pattern for x-z plan.

V. Results

A comparison between the proposed optical delay line and the theoretical HFSS delay has been carried in order to evaluate the proposed technique. Overlapping radiations pattern is possible to compare its performance by analyzing a beam steering from -10 to 20°, as shown in Figs. 9 and 10, respectively. The numerical are very good, since present a great agreement between the proposed technique and traditional electrical feeding network.

In Fig. 10, the antenna array gain is 13.56 dBi for HFSS and 13.76 dBi for optical delay line, both at -10°. At 20° steering angle the gain is 10.26 dBi for HFSS and 8.89 dBi for optical delay line.

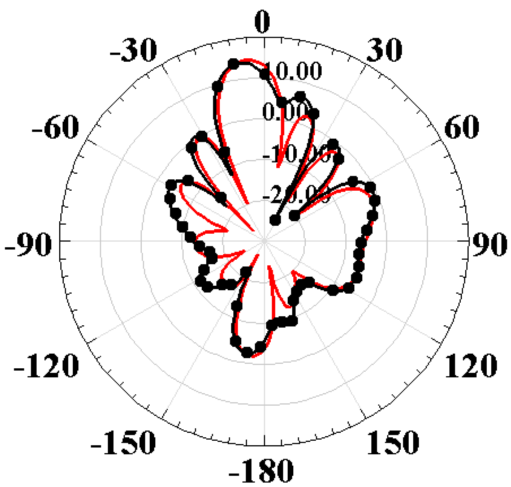


Fig. 10 Radiation pattern for -10° steering angle. Continuous curve from HFSS and circle curve from optical delay line.

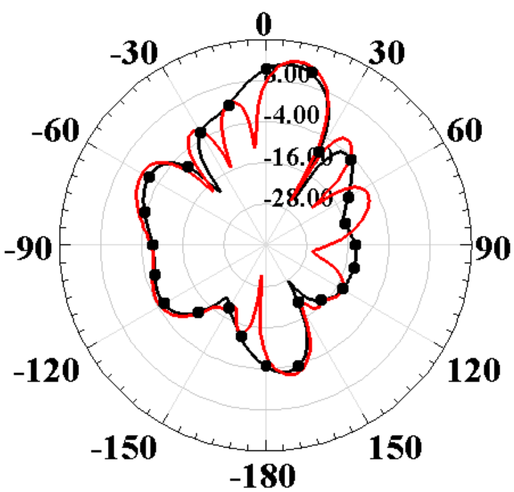


Fig. 11 Radiation pattern for 20° steering angle. Continuous curve from HFSS and circle curve from optical delay line

VI. Conclusions

It has been proposed an efficient design methodology for designing broadband true optical delay lines. It has been validated in the optical domain by VPI and tested electromagnetically in an antenna array at HFSS. We have compared the proposed approach with an ideal electrical delay line, proving its functionality and performance for developing adaptive antenna arrays. Optical and electromagnetic integration between different pieces of software has been proposed and numerically validated.

Future works regards the investigation of the use of different fiber chromatic dispersion and fiber Bragg gratings. Comparison between these techniques is also intended. Finally, a practice validation of the optical delay line with antenna array will be realized.

VII. Acknowledgements

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