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Wide-Band Nulling System for Antenna Array based on a Photonic Microwave Filter and Optical Delay Lines

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Abstract: A nulling system for phased array antennas with broad bandwidth and reduced complexity is presented. The system is based on combining the output of an optical beamforming network with an optical transversal filter steered in the angle where a null is desired in a configuration that reduces the number of optoelectronic conversion compared to previous proposals. Preliminary experimental results to show the feasibility of the concept are provided between 2-6 GHz, showing null depths of 22, 10 and 19 dB at 2, 5 and 6 GHz, respectively.

***Keywords**:* Microwave photonics, Optical Beamforming, Optical signal processing, Antenna Arrays.

1. INTRODUCTION

Over the past decades the use of optics to process microwave signals has caught researchers' attention as a result of the advantages that optical components possess, for example, low loss, large bandwidth, low weight and immunity to electromagnetic interference. Among the different applications proposed in this area, optical beamforming for antenna arrays [1-4] and photonic microwave filters [5-10] have been object of particular wide study due to their potential applicability.

Optically controlled phased array antennas are very attractive due to the benefit of avoiding beam squint (i.e. to provide true time delay, TTD), a problem that arises when large relative bandwidth and/or large antenna arrays are used. In the same way, photonic filters of microwave and radiofrequency signals provide advantages such as large time-bandwidth products, and, especially, tuning and reconfiguration capabilities not shown by traditional microwave filter implementations as well as, the potential to be integrated in a fiber architecture. Moreover, the use of both techniques (optical beamforming and photonic microwave filtering) allows the implementation of a beamformer with the capability to steer nulls in the radiated antenna pattern which is very interesting in several applications (such as radar, communication systems and radio astronomy, among others) where it is necessary to avoid undesired interferences coming from one particular direction while the direction of the main beam is maintained. The advantage of implementing this functionality in the optical domain (over digital and radiofrequency domain) resides in the achievement of wide-band nulls which are limited only by the components used in the implementation of the architecture. Therefore, this optical system will be characterized by its high flexibility in controlling, in a totally independent way, the wide band null direction as well as the phased array steering direction. To achieve this goal, in [11] a wide-band fiber-optic nulling system for array antennas based on a dispersive prism technique was demonstrated. Despite being simpler than previous optically wide-band proposals [12-15], this technique requires two optoelectronic conversions what is a severe impairment to power budget. The assessment of this impairment strongly depends on the particular beamforming scheme as well as the components employed. In general, although analog optical links showing RF to RF gain have been demonstrated in narrow bands [17], there is a tradeoff between bandwidth and gain. Therefore, at present conventional optical beamformers with wide bandwidth show RF to RF loss which can be between a few dB to 30 dB in complex optical beamformers for large arrays [18].

In this letter a different approach is proposed in order to reduce the complexity of the system, i.e, to reduce the number of optoelectronic conversions to just one as usual in analog optical links and thus the system RF to RF loss and nonlinearities can be reduced without losing independent control flexibility.

The paper is divided into four sections. Section 2 provides an explanation of the principle of operation of the wide-band nulling system, as well as a description of the proposed architecture. Next, Section 3 shows the experimental results obtained between 2-6 GHz and finally, a brief conclusion is summarized in Section 4.

2. PRINCIPLE OF OPERATION

The antenna array far-field radiation pattern can be calculated as

$$\vec{E}(\vec{r}) = \vec{E}_0(\vec{r})\sum_{n=1}^{N} a_n e^{i(n-1)(kd\sin\theta - 2\pi f_{RF}\tau)}, \tag{1}$$

where $\vec{E}_0(\vec{r})$ is the element antenna radiation pattern, a_n, the amplitude of the n element antenna, d the separation between antennas, θ the beam steering angle, N the number of elements in the array, f_{RF} the frequency of the modulation, and τ the time delay between antenna elements.

As reported in [19] it is possible to cancel the signal of the array in a desired angle by generating a proper waveform, for instance, by means of an M-tap photonic filter (to benefit from its wide bandwidth)

$$H(f_{RF}) = \sum_{n=1}^{M} b_n e^{-i(n-1)2\pi f_{RF} T_{Filter}}. \tag{2}$$

To achieved this goal, M has to be equal to the number of elements in the array and $H(f_{RF})$ has to be radiated at the angle where radiation null is required

$$\vec{E}_w(\vec{r}) = \vec{E}_0(\vec{r}) \sum_{n=1}^{N} H(f_{RF}) e^{-i(n-1)2\pi f_{RF} T}, \tag{3}$$

where, T_{filter} is the time delay between filter taps and T is the time delay introduced to steer the null. In this way, the superposition of both signals out of phase allows the generation of a null in the desirable direction

$$\vec{E}_T(\vec{r}) = \vec{E}(\vec{r}) + \vec{E}_w(\vec{r}) e^{-i\pi}. \tag{4}$$

If the filter response is properly designed (the number of taps is equal to the number of array elements and the filter taps amplitude is 1/N of the amplitude of the beamformer signal), it reproduces the amplitude response of the radiation pattern at all frequencies. Therefore, when combined out of phase with the output of the optical beamforming network there is no radiation transmitted in the desired angle at any frequency (i.e. a broadband null is obtained).

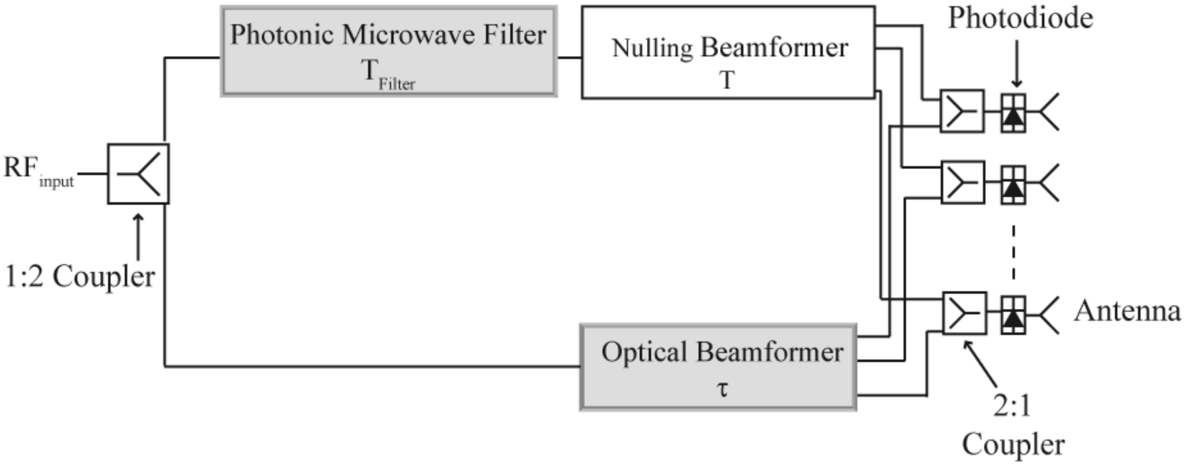

Fig. 1.- General block diagram of the wide-band nulling system.

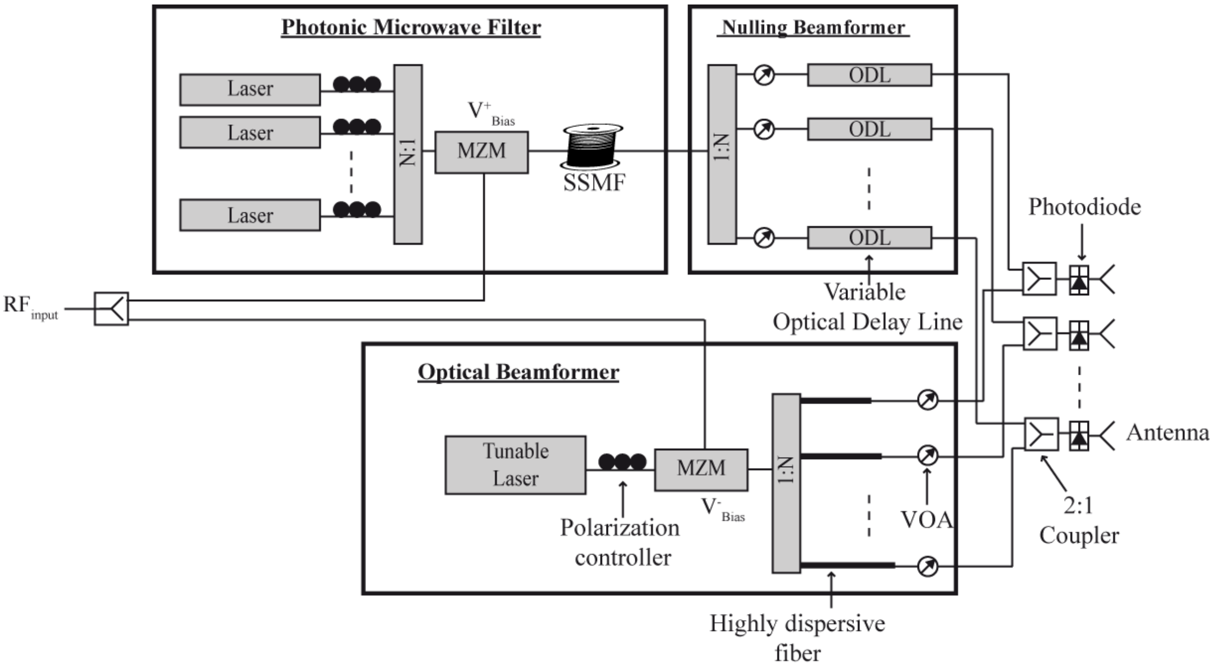

Fig. 2.- Block diagram of a wide-band nulling system based on the proposed technique.

Fig. 1 shows the block diagram of the wide-band nulling system proposed which is composed of two main parts. The first one (lower part of Fig. 2) is the beamformer where the time delay between antenna elements, τ, needed to achieve the beam steering is generated. The second one (upper part of Fig. 2) is the nulling generation subsystem. It is made up of a waveform generator (a microwave filter implemented by a time delay between filter taps, T_{filter}) and the nulling beamformer where a relative time delay between channels, T, is introduced. This beamformer is used to steer the waveform generated by the photonic filter at the direction where the null is required. Note that this technique can be used with any optical beamformer and finite impulse response photonic microwave filter.

Fig. 2 shows a particular example which coincides with the experimental setup carried out to validate the concept. The main beamformer (lower part of Fig 2) is implemented by a dispersive prism made of a combination of highly dispersive fiber or standard single mode fiber and dispersion shifted fiber [16]. By tuning the wavelength of the optical carrier a different time delay profile can be obtained due to the different time delay introduced by the fact that total dispersion in each branch of the prism is different. In this way, different steering angles can be obtained by changing the laser wavelength. On the other side, the optical transversal microwave filter is implemented generating a time delay between taps, T_{filter}, by means of the use of several optical carriers (filter taps) and the chromatic dispersion of a coil of standard single-mode fiber. After the filter, the signal is split in as many paths as antenna array elements and the beamformer used to steer the null is implemented by means of a propagation time delay, T, generated using commercial variable optical delay lines (ODL) .

Taking into account that incoherent operation is employed to avoid coherent interference, to subtract the broadband null signal from the transmitted signal two different Mach-Zehnder Modulators (MZM), one biased at V_{bias}^{-} and the other one at V_{bias}^{+} where employed to modulate R_{input} [9]. In this way out of phase modulation is obtained. Moreover, to control the amplitude of the optical signals a set of variable optical attenuators can be included in the setup as well as, polarization controllers to adjust the state of polarization at the input of each MZM.

Fig. 3 shows the simulated radiation pattern for different frequencies, obtained from (1), assuming a four element antenna (with an antenna spacing of 0.7λ at a design frequency of 6 GHz). In particular, the diagrams have been calculated for a uniform amplitude distribution and a progressive time delay between antenna elements equal to 15 ps, i.e, a beam steering angle of 7.4º.

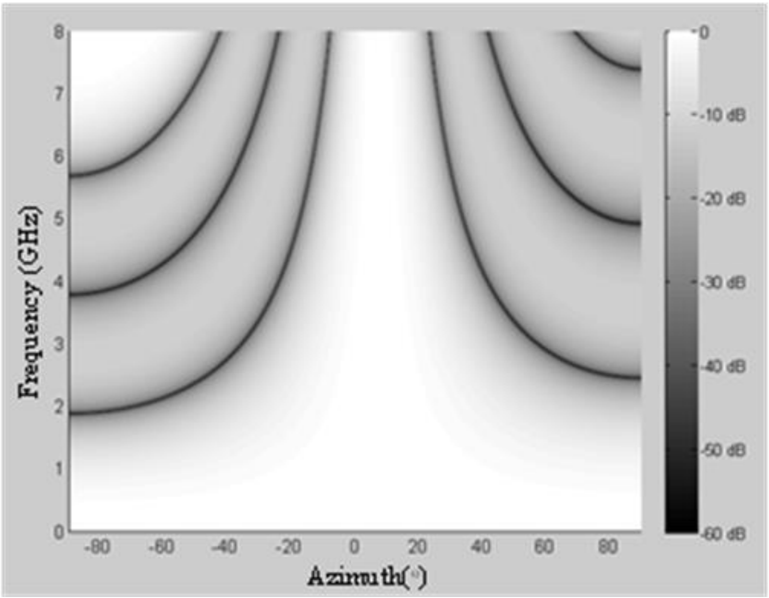

Fig. 3.- Intensity plot of the radiation pattern without null for different frequencies.

In Fig. 4, it can be seen that theory predicts a null at 0º and -27º independently of the operation frequency when a four taps filter with a progressive time delay of 15 and 68 ps, in that order, is combined out of phase with the beamformer, with T equal to 0 and -53 ps respectively. As can be seen from the results, it is possible to steer nulls whereas the main beam steering angle remains unchanged as the frequency is varied.

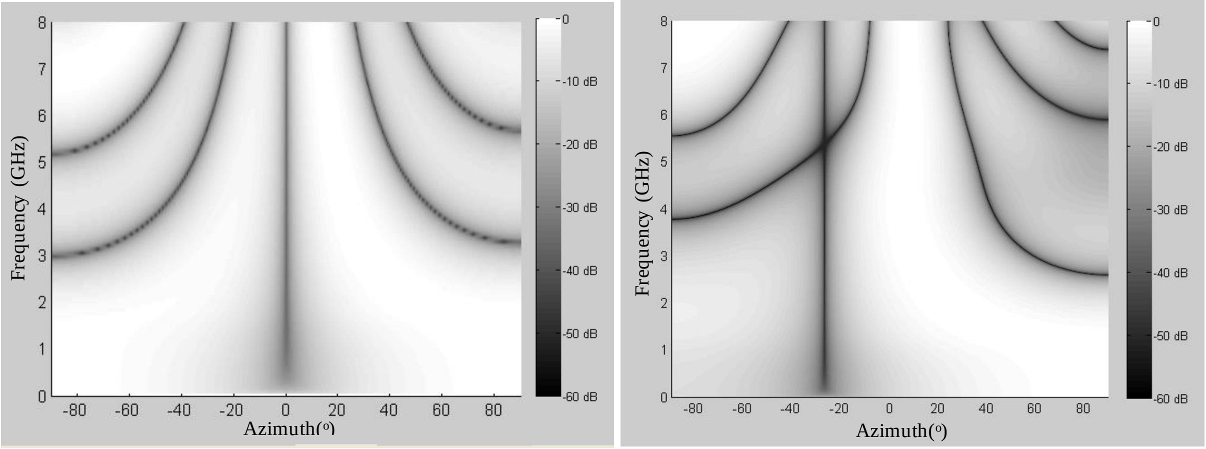

Fig. 4.- Intensity plot of the radiation pattern with null at 0º and -27º for different frequencies.

3. EXPERIMENTAL SETUP

To show the validity of the concept preliminary experiments have been carried out using the setup shown in Fig. 5.

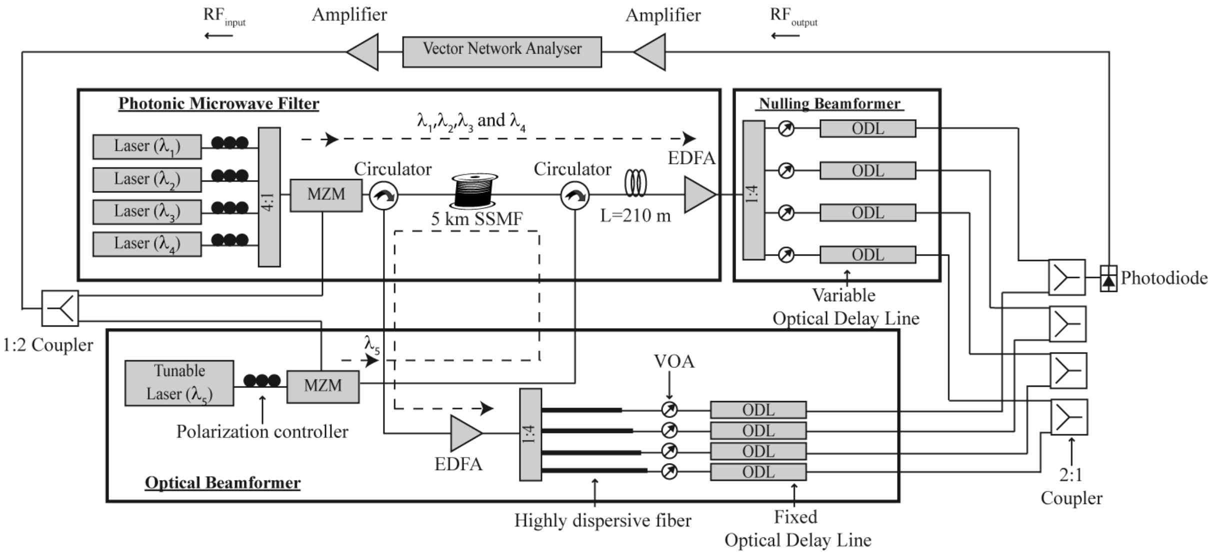

Fig. 5.- Experimental setup.

The architecture chosen was the same depicted in Fig 2, where the optical transversal microwave filter has been implemented using multiple optical carriers and chromatic dispersion of a coil of 5 km of standard single-mode fiber with D = 17 ps/(nm km). Two erbium-doped fiber amplifiers (EDFA) were included to compensate for the loss of the fiber coil. Moreover, the propagation time delay between the upper and lower parts of Fig 2 have to be equal, therefore two circulators and a fiber pigtail of 210 m have been introduced. Additionally, for the sake of convenience, ODLs were used to finely adjust the time delay of each one of the parallel beamformer paths instead of splicing fiber patchcords of proper length.

The optical insertion loss of the entire system was around 14 dB (taking into account EDFAs with a gain of approximately 17 dB). However the aim of this experimental setup was just to proof the concept and loss was not optimised. In any case, due to the need of only one optoelectronic conversions the RF to RF loss is reduced roughly by half using the new approach compared to prior art where two optoelectronic conversions are used.

To demonstrate the principle of operation measurements using the setup of Fig. 5 were done. To show wide-band operation, measurements were carried out at different frequencies (2, 5 and 6 GHz). The optical beamformer was designed to steer the main beam to 0º when the laser would be set at 1545.82 nm and to direct the beam to 7.4º when the wavelength would be decreased 3.7 nm, i.e, a time delay between antenna elements approximately equal to 15 ps.

To achieve a null at -27º, a photonic finite impulse response filter with a time delay between taps (T_{filter}) of 68 ps (FSR= 3.6 GHz as shown in Fig.6) was implemented using four independent lasers (taps) spaced 0.8 nm (1550.92, 1550.12, 4549.32 and 1548.52 nm). Next, each filter response was delayed with a progressive time delay (T) of -53 ps (Fig. 7).

On the other side, Fig. 8 shows the radiation patterns obtained from the amplitude and phase measurements in each branch of the optical beamformer using a vector network analyzer, assuming a four element antenna array where the spacing between them is set at 0.7λ and the design frequency is 6 GHz. In particular, Fig.8a, 8c, and 8d depict the radiation pattern without null (dotted line) and the waveform generated (dashed line) by the optical beamformer and the nulling system of the architecture, respectively at 2, 5 and 6 GHz. Fig. 8b, 8d and 8e compare the diagram without null (dotted line) and with null (solid line). As can be seen from these graphs, nulls with a deep of, approximately, 22, 10 and 19 dB are achieved around -27º at different frequencies 2, 5 and 6 GHz, which show that by using this technique a wide-band squint free nulls can be achieved.

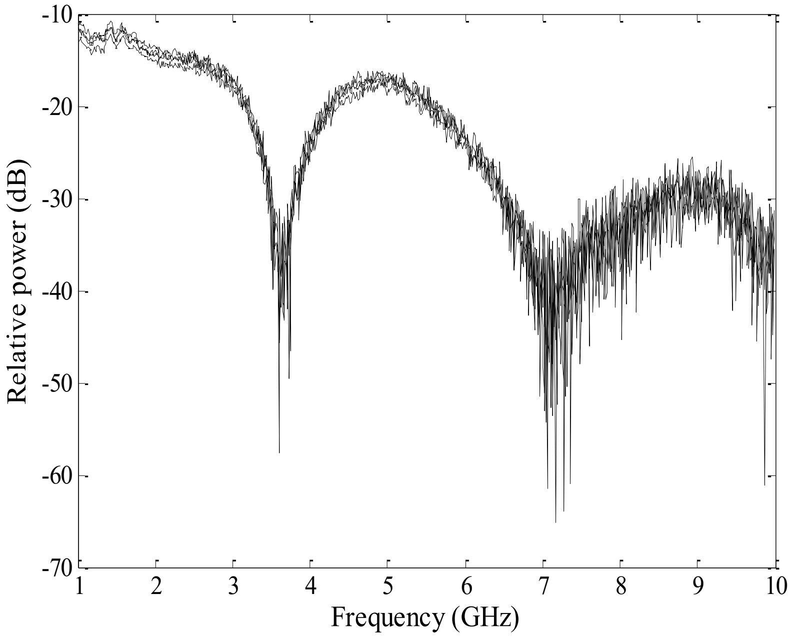

Fig. 6.- Filter responses obtained in each branch of the nulling control system.

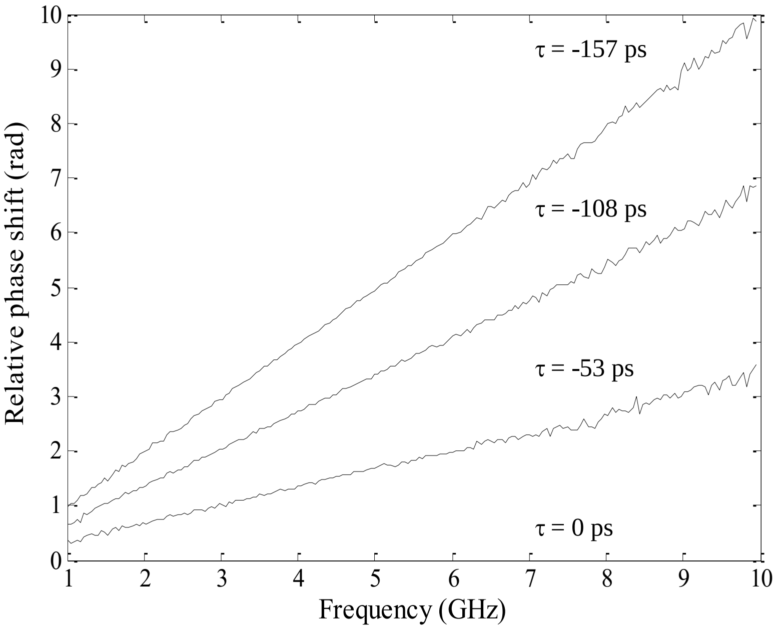

Fig. 7.- Measurement of the time delay between the branches of the nulling control system.

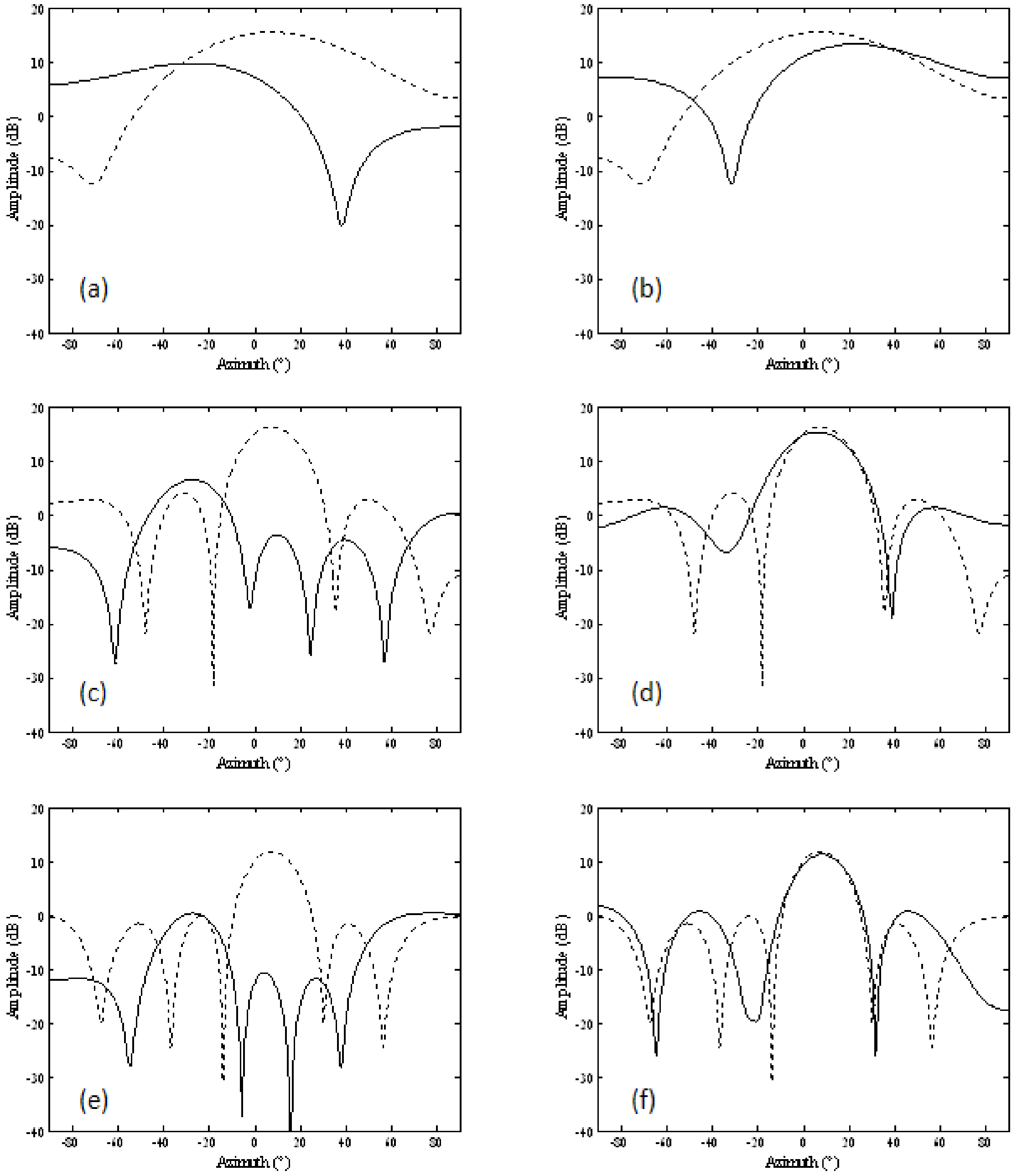

Fig. 8.- Representation of the radiation pattern without null generated by the optical beamformer (dotted line) and the waveform to achieve a null at -27° (solid line): (a) at 2 GHz, (c) at 5 GHz and (e) at 6 GHz. Comparison of the radiation pattern with null (solid line) and without null (dotted line): (a) at 2 GHz, (c) at 5 GHz and (e) at 6 GHz.

In light of the results obtained, the validity of the proposed null system to generate nulls and the wide-band operation is confirmed. It can be seen that there is a slight variation in the depth and angle of the null caused by errors in the amplitude measurement.

4. CONCLUSION

A wide-band nulling system for phased array antennas based on a photonic filter and optical delay lines has been reported. Radiation patterns estimated from amplitude and phase measurements, between 2 and 6 GHz, for a four antenna beamformer have been provided to demonstrate the feasibility of the architecture. The results show a good agreement with theory with wide band nulls of 22, 10 and 19 dB at 2, 5 and 6 GHz, respectively. Measurements show the capability of the technique to achieve wide-band nulls while reducing both complexity and system RF to RF loss when compared to previous wide-band nulling architectures.

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