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Improved Photonic True Time Delay Unit for a Ku-Band Phased Array Antenna Demonstration

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Abstract: In this letter, a Photonic True Time Delay (PTTD) unit for phased array antennas is experimentally demonstrated. The PTTD unit, employing a single wavelength laser source, exploits the distributed photonic bandgap offered by a Linearly Chirped Fiber Bragg Grating (LCFBG) to attain different time delays by properly actuating the physical and geometrical features of the LCFBG through temperature changes. The time delay response of the TTD unit has been measured experimentally revealing multiband operation capability (S, C, X and Ku bands) with ps time delay resolution and a maximum dynamic range of 250ps. The time steering demonstration has been performed by characterizing in the Ku band an array prototype within a Near Field range.

INTRODUCTION

Photonic true time delay (PTTD) lines, providing a controlled time delay for an optical signal, are required in several applications ranging from all-optical communication systems to microwave photonics [1]. In the last decade, there has been growing interest in the employment of photonic true time delay techniques for the beamsteering of phased array systems in light of the squint free wideband capability they offer along with the classical advantages of photonic technology. Many kinds of photonic TTD lines have been proposed involving either path switching [2, 3] or dispersive techniques [4-6]. The techniques relying on path switching principle, even if typically present high time delay precision and stability, provide only discrete time delay increments. Inversely, the employment of dispersive elements, together with tuning capability, allows to achieve continuous beamsteering and multiband operation. In many proposals, Linearly Chirped Fiber Bragg Gratings (LCFBG) have been used as dispersive element and continuous time delays have been obtained by tuning the wavelengths of different laser sources [4, 5] or by tuning mechanically the grating features [6]. Nevertheless, the employment of a single wavelength laser source and the lack of moving mechanical elements would be the best solution in terms of robustness, reduction of costs and system complexity.

Recently, we proposed a technique to enable optical control of Phased Array Antennas (PAAs), employing a single wavelength laser source and a low cost LCFBG temperature control system, allowing to achieve a continuous true time delay by changing uniformly the temperature of the LCFBG [7, 8]. The first prototype realization led to the individuation of critical points in the proposed configuration that, while demonstrated the 2GHz operation capability, suffered the high non linearities of the LCFBG group delay as well as of a reduced bandwidth. The LCFBG group delay non linearities in fact lead to a worse resolution on the time delay values, limiting in practice also the maximum microwave frequency allowed, cause of the lower time delay resolution required at higher frequencies in PAAs applications. On the other side the LCFBG bandwidth directly limited the maximum time delay allowed, being the mean dispersion yet established to meet the time delay resolution requirements [7, 8]. The previous analysis, hence, suggested that in order to enhance the PTTD unit performances, in terms of maximum operating frequency, time delay resolution and time delay dynamic range, a LCFBG with a linear group delay, low dispersion and low ripple along a wide bandwidth should be provided and the same features should be basically maintained also during the thermal tuning. In the current work, the proposed principle of operation, and thus the low cost fabrication procedure involved, has been adopted again to realize the PTTD line but special care has been devoted to the LCFBG features in terms of group delay ripple and bandwidth and to the actuating system in terms of uniformity of the temperature profile in a wider temperature range. The fabrication improvements and performance advances of a PTTD line are described in details in this letter and the differences with respect to the previous work are also outlined. Finally, the multiband squint-free beam steering capability of the realized PTTD line for PAAs is reported.

TIME DELAY UNIT

The photonic true time delay line is basically constituted by a LCFBG bonded on a metallic support and actuated by a temperature control system as schematically reported in Fig. (**1a**). LCFBGs are a class of Fiber Bragg Gratings basically

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characterized by a period varying linearly along the grating length. This physical features, while gives rise to a stop band in the spectrum, leads to a linear group delay response as reported in Fig. (**1b**). The PTTD unit basically enables the time delay tuning of a single wavelength optical signal reflected within the LCFBG bandwidth by exploiting the spectral shift of the distributed photonic bandgap offered by a LCFBG experiencing an uniform thermal change. As matter of fact, a temperature change, modifying the physical features of the grating by means of thermo-optic effect and the thermal expansion, leads to a variation of the round trip time of a single wavelength optical signal reflected by the LCFBG itself in such a way that the time delay will be linear proportional to the set temperature.

The LCFBG used for the PTTD presents a length of 7.7cm and central Bragg wavelength of 1550nm (at room temperature).

The LCFBG has been bonded on a metallic support with size 1.0x9.0x0.1cm^3, in order to facilitate the achievement and the uniformity of the desired LCFBG temperature, exploiting the thermal diffusion of the metal, and to increase the LCFBG thermal sensitivity in terms of wavelength shift per temperature degree [8]. The temperature system control relies on a PID control and 9 Peltier cells of 9x9mm^2 bonded on the metallic support on the opposite side of the LCFBG and properly spaced in order to guarantee an uniform temperature profile, since any thermal non uniformity could degrade the group delay linearity features of the LCFBG. From the electrical point of view, the Peltier cells have been connected in a hybrid (series and parallel) configuration in order to improve their reliability in long time usage. The resulting low cost temperature control system is able to supply continuous temperature variations in the range 10-80°C with 0.1°C resolution.

The PID control parameters have been chosen to optimize the minimum overshoot in spite of the minimum time to reach the set-point temperature, in order to guarantee a stable steady state. The time needed at the temperature control to reach the set-point ranges from about 2 seconds for a temperature variation of 0.1°C up to about 50 seconds for the maximum temperature excursion. Nevertheless, the time the controller takes to reach the set-point, and thus the response time of the PTTD unit, could be strongly decreased by reducing the heat capacity of the metallic support either by reducing its volume or by substituting it with a thin film heater uniformly deposited onto the LCFBG in which the temperature is changed by applying a suitable voltage on it [9]. Alternatively, the same principle of operation could be adopted to realize PTTD units based on a strain actuating system as envisaged yet in ref. [7].

The LCFBG bonded on the metallic support has been spectrally characterized at controlled temperatures in terms of reflectivity and group delay through the modulation phase shift method at 300MHz [10]. The LCFBG spectrum, retrieved at 30°C and shown in Fig. (**1b**), presents a full width half maximum (FWHM) bandwidth of 5.0nm, a mean dispersion of 100.5ps/nm, and a mean amplitude of the group delay ripple of just 1.5ps. The same characterization, performed for several temperatures, revealed that the thermal sensitivity of the LCFBG results in about 40pm/°C. The availability of a linear group delay with low dispersion and low ripple along a bandwidth as wide as 5nm constitutes the key feature to improve the device performances. Here, the employed LCFBG was fabricated by using an holographic writing technique able to provide lower group delay ripple and at the same time a wider bandwidth with respect to the previous work [8] in which the LCFBG demonstrated 3.8ps ripple in 1.6nm bandwidth limiting the device performances.

EXPERIMENTAL RESULTS

The TTD line has been characterized through S-parameter measurements in the RF frequency range 2-18GHz and in the 10-80°C temperature range. The experimental setup basically employs a vector network analyzer (VNA) to measure the phase shift introduced by the PTTD unit. To the aim, a single wavelength optical signal (1550nm) is sent to a Mach-Zehender electro-optic modulator through a polarization controller. The optical signal, modulated through the RF signal provided by the VNA, is sent to the PTTD line and back-reflected towards a photodiode connected to the VNA itself.

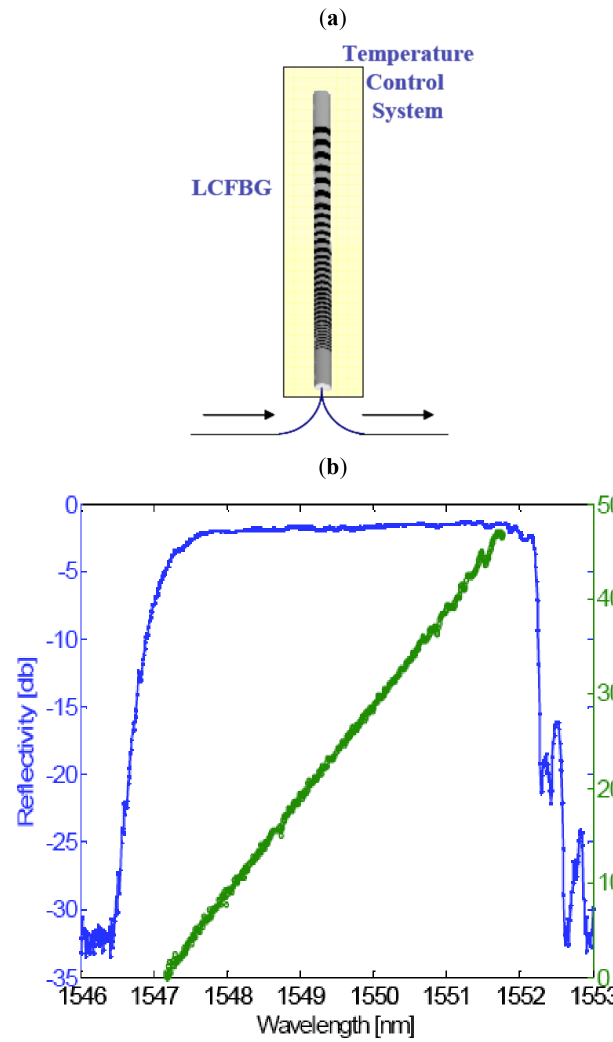

Fig. (1). Schematic view of the PTTD unit (**a**). LCFBG reflectivity and group delay of the LCFBG at 30°C (**b**).

In Fig. (**2**) the time delay characteristics versus the temperature of the TTD line, extracted from the S21 measurement [10], are reported. The characteristics have been retrieved in the temperature range 10-80°C with 0.1°C steps for different operating frequencies. In particular, the characteristic curves plotted in Fig. (**2**) have been carried out at the RF frequencies 2, 10 and 18GHz. For sake of clarity, the three curves, covering the whole investigated RF frequency range, have been translated in order to allow a more clear visualization, by avoiding their superposition.

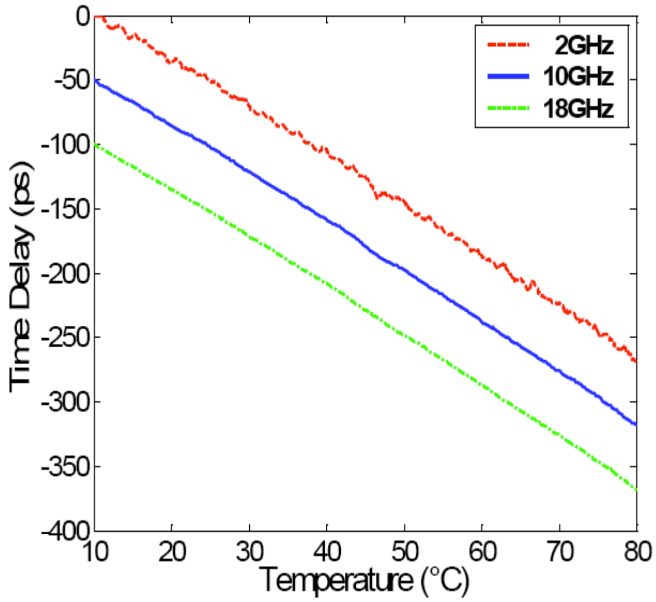

Fig. (2). Time Delay-Temperature characteristics of the TTD line retrieved at 2, 10 and 18GHz.

For all investigated frequencies, the time delay-temperature characteristics offer an almost linear behavior, well described by a straight line with mean slope of about -3.8ps/°C, and allow a maximum time delay excursion of more than 250ps with picosecond resolution.

Small differences are observable among the curves retrieved at different RF frequencies. In fact, the measurements performed at lower frequencies demonstrated higher non linearities, in particular, the mean deviation from the linearity of the characteristics decreases from about 1.9ps down to 1.3ps as well as the RF frequency increased.

It is worth noting that the proper choice of the LCFBG features together with the careful realization of the temperature control system enhanced the PTTD performances with respect to the previous work [8], either in terms of time delay maximum excursion or in terms of linearity features. As matter of fact, the comparison (allowed at 2GHz) demonstrates that the maximum time delay excursion has been more than doubled without degrading the linearity of the characteristic, that results to be also improved, in an extended range of controlled temperatures.

In order to further demonstrate the wideband capability of the realized TTD line the S-parameter measurements have been also performed in the frequency sweep mode at different temperatures. In Fig. (**3**) the phase of the delayed RF signal is reported with respect to the RF frequency. The phase shift introduced linearly depends on the RF frequency with a slope related to the set time delay demonstrating that the realized TTD enables a true time delay and that the set temperature determines the delay experienced by the RF signal without dependence on its frequency, as theoretically and numerically envisaged in ref. [7]. In addition, the time delay variations with respect to the set value, representing the nominal time delay, are always less than 1.1ps demonstrating the PTTD wide bandwidth operation capability.

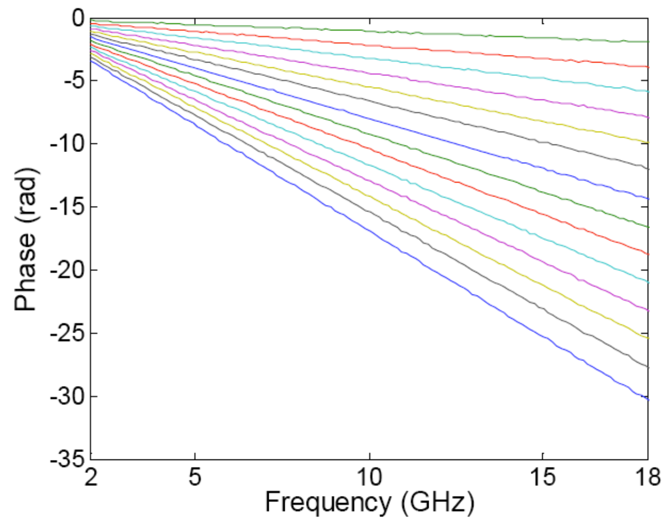

Fig. (3). Phase versus RF frequency for different set temperatures. Different lines correspond to different temperatures starting from T=10°C and increasing up to T=80°C in constant intervals of 5°C.

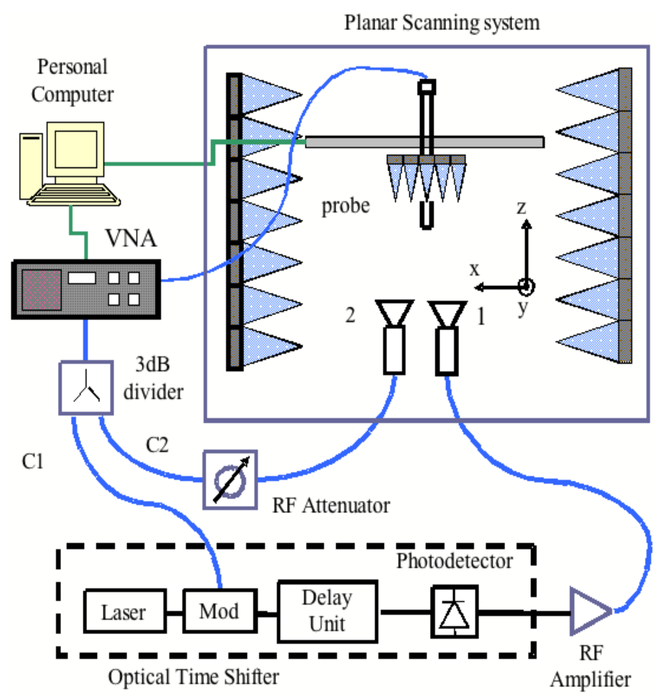

Fig. (4). Experimental setup for the beamsteering proof.

It is worth noting that the time delay resolution in the picoseconds range is greatly required in PAA wide bandwidth applications as well as a wide time delay dynamic range is required when an high number antenna elements are needed. Specific quantitative requirements on the PTTD line for PAA systems actually depend on several factors such as the number of array elements, the required maximum and minimum scanning angle, the antennas elements distance as well as the operating frequency range. Nevertheless, as

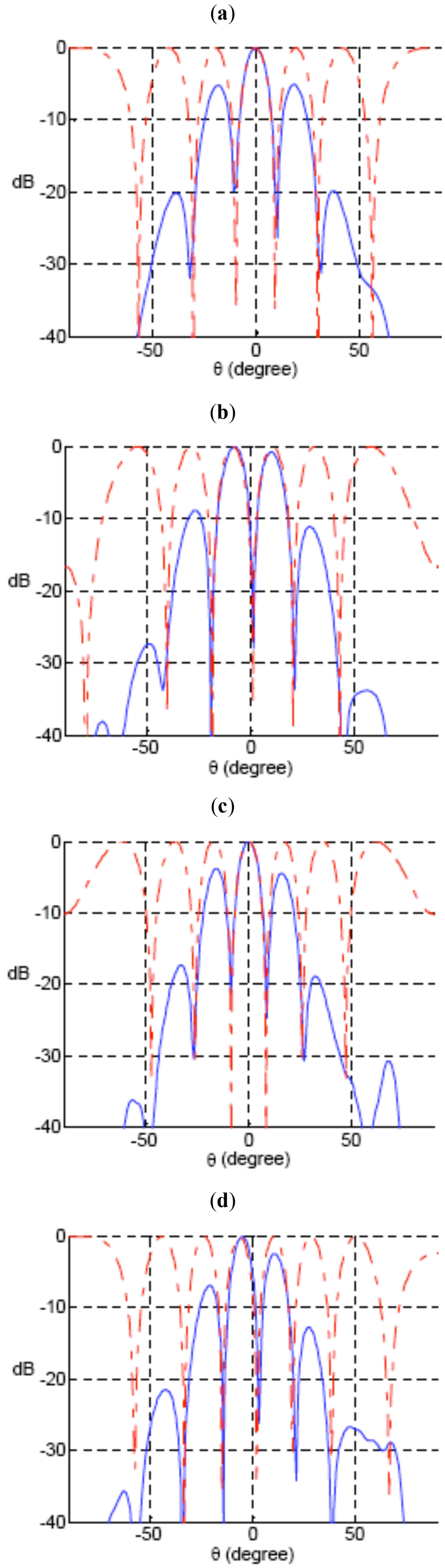

Fig. (5). Theoretical amplitude of the array factor (dashed line) and measured field pattern (solid line) at 15GHz for θ_0=0º (**a**) and θ_0=10º (**b**) and at 17GHz for θ_0=0º (**c**) and θ_0=10º (**d**).

general trend, it can be stated that the best for a PTTD line for PAAs is to achieve fine time delay tuning capability (for instance, few picoseconds typically allows to work at tens GHz) with a wide time delay dynamic range (i.e. up to nanoseconds for large PAA systems). In order to exploit the proposed PTTD unit to control very large PAA systems with a high number of elements (hundreds or more), maintaining the time delay fine tuning capability, the LCFBG bandwidth should be increased through an increase of the LCFBG length or alternatively a different strategy could be adopted, by employing a cascade of delay lines with different time delay resolution. The former one to set large time delays (i.e. with hundreds picoseconds steps) and the latter one to finely tune the time delay around the coarse time delay step.

Finally, an experimental beam steering proof has been performed. A two elements array prototype working in the Ku band has been considered. The radiating system configuration and the measurement setup have been designed to improve the near field measurements accuracy and to efficiently demonstrate the beam steering. In particular, two pyramidal horn antennas, working in the Ku band have been considered, allowing a reduced truncation error in the near-field measurements with a reasonable scanning area. Furthermore, a large radiating element distance, equal to 6cm, has been set to improve the beam steering angle estimation, based on the evaluation of the position of the pattern nulls. The characterization procedure has been realized by using the measurement setup depicted in Fig. (**4**). Near field data are collected by using a remotely controlled planar scanning system, a Vector Network Analyzer (VNA) and a PC controlling synchronously probe movements and VNA acquisitions. The scanner (Physik Instrumente model M-417.40) allows a 60cmx60cm scanning area and the VNA is Anritsu 37377C.

The environmental reflections have been reduced by properly introducing anechoic panels. Concerning the feeding network, the microwave signal generated by the VNA is split in two signals, as shown in Fig. (**4**), by means of a 3dB divider. The signal C1 feeds the PTTD line, experiencing the desired delay, and is amplified to compensate for the conversion losses. The signal C2 is controlled by means of a variable attenuator to balance the microwave signals levels. The measuring probe is an open-ended waveguide. The beam steering demonstration has been performed at 15GHz and 17GHz for several beam pointing angles θ_0 (evaluated with respect to the normal of the horn aperture). In this letter, the results related to two beamsteering configurations (θ_0 =0º and θ_0=10º), for both frequencies are reported.

For both cases, the following measurement procedure has been adopted. Firstly, the two antenna channels have been calibrated by properly acting on the attenuation level on path C2 and the time delay on path C1, balancing the amplitudes and phases at the inputs of the radiating elements.

In order to steer the beam, the appropriate LCFBG temperature has been set according to the time delay temperature characteristics.

For both frequencies, the near field data have been acquired by considering both the polarizations. At 15GHz, an acquisition area of 27 λ x25 λ, located at a distance z=10λ, has been used, while at 17GHz, a 30 λ x30 λ area at z=11.3 λ has been employed. Data have been uniformly sampled in both the x and y directions, with step equal to λ /2 (Fig. **4**).

The near field data have been processed by means of a Near Field-Far Field transformation algorithm accounting for the probe behavior and filtering the environmental clutter. The measured field patterns at 15GHz are reported in Fig. (**5a**,**b**) for the configurations θ_0=0º and θ_0=10º respectively, while the Fig. (**5c**,**d**) refers to the 17GHz measurements.

In order to check the steering capability of the feeding network and its performance with respect to the frequency variations, the investigation has been focused on the positions of the nulls of the far-field pattern and a comparison with the theoretical array factor, say F(θ) evaluated according to the analytical expression:

$$F(\theta)=\sum_{n=1}^{N} C_n e^{j\beta nd\cos(\vartheta)} \qquad (1)$$

β being the propagation constant, d the inter-element distance, N the number of elements and C_n the excitation coefficients. As comparison, the amplitude of F(θ), corresponding to the nominal values of the excitation coefficients, is reported in Fig. (**5a**,**d**). Obviously, only the comparison between the nulls postions is meaningfully.

It is noted that a good agreement between theoretical and experimental results is achieved, demonstrating the beam-steering capability of the PTTD line. Furthermore, being the PAA scanning angles not meaningfully dependent on the microwave frequency, Fig. (**5**) also demonstrate, once again, the squint free operation of the realized PTTD line in the Ku band.

CONCLUSION

In this letter, an improved PTTD unit for PAAs based on a temperature controlled LCFBG has been presented. The device operates at a single optical wavelength and the time delay is tuned by changing uniformly the temperature of the LCFBG. The PTTD line enabled time delay control with a resolution of about 1ps, employing a temperature controller with a stability of ±0.1°C and a maximum time delay of 250ps over a temperature range of 10-80°C. The time delay-temperature characteristic presented a mean slope of -3.8ps/°C with a linearity deviation in the ps range. Also the wide bandwidth and squint free operation capability from 2 up to 18GHz has been demonstrated. Finally, the PTTD unit steering capability has been proved at 15GHz and 17GHz.

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