Demonstration of super-Gaussian apodized linearly chirped fiber Bragg grating for efficient beam steering in Ku-band applications

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1  |  INTRODUCTION

Photonic true-time delay (TTD) has been extensively investigated as a promising technique for wideband phased array antenna (PAA) system [1] in comparison to electrical TTD, although both systems are immune to the problem of beam squint. Credit goes to the inherent properties of optical fibre, that is, immunity to electromagnetic interference, low propagation loss, huge bandwidth, remote capability and simplified transmitter/receiver (T/R) modules. Nowadays, several configurations of photonic TTD systems have been reported for beam steering, such as, in [2–4]; the authors used systems based on bulk optics, serial delay lines, parallel delay lines, integrated silica-waveguide switches that offers high insertion losses in comparison to fiber Bragg grating (FBG) prism [5, 6], chirped FBG (CFBG) [7, 8], a combination of FBGs and CFBG. Here, the focus is on beam steering using FBG as they offer low polarization dependent on loss and low insertion loss.

In [9], the author proposed a photonic system that assures broadband operation, but it only allows a discrete number of beam pointing angles and also it is suitable only for microwave frequencies less than or equal to 6 GHz. Subsequently, to achieve continuous beam steering [10] at higher microwave frequencies [11], chirped FBGs [12] or chirped grating-based prism may be used in the optical beamforming network. Chirped FBG array [13–15] based on the technique of photonic beam steering of phased array antenna, working in transmitting and receiving mode has been demonstrated in [16]. In spite of continuous beam steering, CFBG-based system suffers from the problem of high ripples [12] in reflection spectrum which gives rise to ambiguities in delay when laser is tuned to particular wavelength. To solve this problem, various apodized profile for FBGs have been proposed to reduce the sidelobes responsible for high ripples in reflection spectrum [17–19]. In [3], the authors presented a sinc apodized multichannel chirped FBG based on dynamic TTD wideband beam control module with the assistance of a four-element antenna array. They showed that by reducing the channel spacing and channel bandwidth, as well as increasing the grating length, the number of elements that can be supported within an antenna array could be increased. But this results in decrease in channel reflectivity due to saturation of the available refractive index.

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change in the fibre. Here, we illustrate a wideband optical beamforming network consisting of eight SGFBGs of distinctly size and a chirp parameter, which regulates the scanning direction by generating a linear phase delay of the modulating signal at microwave frequencies, making it possible to continually adjust the inclination of the phase response by adjusting the optical source wavelength. Chirped FBG with a unique featured apodization profile has been manufactured using the Cu-vapor laser-based second-harmonic generation method in our collaborative laboratory. In FBG writing, a special featured phase mask was used to produce a raised cosine form of refractive index profile at the fibre core that generates almost negligible group delay ripples resulting in linear delay change by tuning at the corresponding laser wavelength. In Section 2, step-by-step theory with proper simulation results for PAA has been presented. Section 3 presents a promising technique known as TTD, to eliminate the problem of beam squint faced by PAA. The experimental setup of photonic TTD module has been covered in Section 4. Section 5 presents results and discussion, followed by the conclusive remark in Section 6.

2 | N-ELEMENT LINEAR ARRAY OF PHASED ARRAY ANTENNA

For the purpose of simplifying the theory, only uniform linear arrays will be considered to give a brief idea on the far-field radiation pattern of phased array antenna. An array of identical elements having identical magnitude and each with a progressive phase is referred to as a uniform array. The radiated field of an array essentially is the summation of the individual element fields. It can be shown that the far-field pattern of an array of identical elements can be represented by a product of two quantities, namely the element pattern and the array factor. The element pattern signifies the radiation behaviour of an individual element and the array factor (AF) signifies the arraying effect, including array architecture and relative excitations of the elements [20]. Here, the discussion mainly revolves around the AF for the purpose of simplicity; therefore, the generalized AF of N-element PAA can be written in a normalized form as [21]:

$$ (A.F.)_N \equiv \left[ \frac{\sin \left( \frac{N \psi}{2} \right)}{N \sin \left( \frac{\psi}{2} \right)} \right] $$

(1)

here $\psi = k.d \sin(\theta) + \beta$, $k = \frac{2\pi}{\lambda}$, $k$ is the spatial angular frequency of the wave and $\lambda$ is the free-space wavelength.

Before going into details on the various concepts of phased array antenna in the context of beam steering, it is very important to understand the effect of antenna element spacing on the far-field radiation pattern. As we know that AF is a periodic function, therefore, by applying the Nyquist theorem of signal processing theory, if the elements in phased array antenna are not properly sampled with correct element spacing, will ultimately results in generation of grating lobes (as shown in Figure 1). Grating lobes are basically periodic copies of the main beam and their locations are a function of frequency and spacing between elements. Grating lobes are special case of sidelobes. Thus, all the lobes lying between the main lobe and first grating lobe can be considered as sidelobes. Based on the concept of phased-array antenna theory, for avoiding the problem of grating lobes in the radiation pattern of antenna, the consecutive spacing $(d)$ between elements of the N-array antenna system, must obey the given condition:

$$ d \leq \frac{\lambda_{RF}}{1 + |\sin \theta_{\text{max}}|} $$

(2)

here $\lambda_{RF}$ is the free space wavelength of the RF wave and $\theta_{\text{max}}$ is the maximum scanning angle. After assuming $\theta_{\text{max}} = \pm 90^\circ$, Equation (2) will become $d \leq \frac{\lambda_{RF}}{2}$.

One can easily observe the above concept in Figure 1. From Equation (1), it is very clear that by varying the separation between each element of antenna array, the phase progression between the angle and by changing the number of elements in antenna array system, the angle and slope of the main lobe of the antenna, $\theta_c$, can be managed.

3 | NEED OF TTD MODULE

The phase of each input signal is governed by phase shifters for each PAA element, which presents a set necessary phase value. Over the previous few decades, various methods have been proved and checked to realize such component types. Device tunability is the most significant factor responsible for raising the complexity level in the phase shifters. Conventional phase shifters add a certain quantity of phase shift to each signal, regardless of the frequency of the feed signal [9]. One of

![Figure 1](https://example.com/image1.png)

**FIGURE 1** Normalized radiation pattern of antenna when the spacing between elements is $\lambda$. 

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the primary obstacles in the path of this technology is the well-known phenomenon called ‘beam squint’, which is liable for signal distortion. Beam squint is the phenomenon where the main lobe of the normalized AF is directed at different angles, \( \theta \), for signal with different frequency. In other words, the energy corresponding to the respective frequency is aimed in various directions, eventually limiting antenna deployment in narrow-band region.

Figure 2 demonstrates the far-field radiation pattern of the AF for a frequency range of 10 to 18 GHz with an interval of 2 GHz for a phase progression of \( \beta = \pi/4 \). In Figure 2, 16 elements antenna array with separation of 15 mm between each element. Antenna operation in the frequency range of 10–18 GHz is researched to show the impact of beam squint. One can easily observe from Figure 2, that the angular direction of the main lobe changes with the change in input signal frequency. This phenomenon, that is, beam squint considerably degrades the communication system’s general efficiency. Figure 2 shows that the main lobe orientation ranges from 20° to 35° over the range of observed frequencies (10–18 GHz). The most promising technology to eliminate the issue of beam squint is TTD.

TTD is a method of providing a constant time delay, \( \Delta t \), for the entire frequency range, which in turn is translated into a linear phase shift with respect to frequency [9]. The time delay introduced by TTD unit does not vary with the frequency; thus, a constant time delay is converted into variable phase shift with respect to frequency based on the expression [3]:

\[
\beta = 2\pi f \Delta t
\]  

In Figure 3, PAA is used with the same requirements as conventional phase shifters, but now TTD module instead of standard phase shifters has been implemented. The element in these modules will induce a time progression of \( \Delta t = 12.5 \) ps which corresponds to the phase of \( \pi/4 \) at a frequency of 10 GHz. One can easily observe from Figure 3, that the direction of the main lobe does not vary with the feed signal frequency rather the angle of main lobe remains exactly at the designed angle of 18.23°. Thus, by changing the time delay, the main lobe angle can be varied. Perhaps the angle of main lobe can be varied by adjusting the time delay.

Figure 4 shows the schematic of four equally spaced (with distance \( d \)) elements of PAA. The phase difference \( \Delta \phi \) between the signals applied to adjacent elements controls the steering angle of \( \theta \). Each PAA element transmits the electromagnetic field which becomes an individual plane wave in the far-field region. The plane wavefronts will interfere constructively in the desired direction of \( \theta \). If the \( \Delta \phi \) corresponds to the path-length difference of \( d \sin \theta \) between adjacent elements. Therefore, the \( \Delta \phi \) required to steer the beam towards a given direction \( \theta \) is:

\[
\Delta \phi = \omega t = \frac{2\pi f L}{c} = \frac{2\pi f d \sin \theta}{c}
\]

where \( f \) is the frequency of the microwave signal and \( c \) is the velocity of an em-wave. As we know that the time difference (time delay(\( \Delta t \))) can be calculated as:

\[
\Delta t = \frac{\Delta \phi}{2\pi f} = \frac{d \sin \theta}{c} = \frac{\sin \theta}{2f}
\]  

**FIGURE 2** Beam squint effect for PAA operating at frequencies between 10 and 18 GHz. PAA, phased array antenna

**FIGURE 3** Far-field radiation pattern of PAA employing the concept of TTD operating in the frequency range of 10–18 GHz. PAA, phased array antenna; TTD, true-time delay
Thus, to control the steering angle it is important to carefully design the chirped grating with the correct parameters to get the required value of $\Delta \tau$.

### 3.1 FBG fabrication

The formula combining a grating shape, an average index modulation function, a period chirp function, and an apodization function can represent a grating function [22]:

$$n(x, y, z) = n_0(x, y) + \Delta n_0(x, y, z) + \Delta n.P(x, y).A(z).$$

$$f\left(\frac{\Lambda(z)}{\cos \theta}, z\right)$$

where $n_0$ is the refractive index of waveguide, $\Delta n$ is the index modulation amplitude, $\theta$ is the grating tilt angle, $\Lambda(z)$ is the period of chirp function, $\Lambda(z)$ is the apodization function, $f\left(\frac{\Lambda(z)}{\cos \theta}, z\right)$ is the shape function, $P$ is the waveguide’s photosensitivity profile. In Equation (2), the average index modulation feature $\Delta n_0$ is only implemented in the grating region, that is, in non-zero photosensitivity layers. Layers with very low photosensitivity will react to the modulation of average index, but the grating will be very weak there. Following parameters were considered here while designing RCFBG:

$$\begin{align*}
\theta &= 0^0 \\
\Lambda(z) &= \Lambda_0 - \frac{z - L}{L} \\
A(z) &= \exp\left(-\left(\text{temp} \times \left(\frac{x - L}{L}\right)^m\right)\right) \\
\text{temp} &= 2 \times \left(\text{pow}(\ln(2), \frac{1}{m})\right) \\
W &= \frac{L}{2} \\
m &= 4
\end{align*}$$

In Equation (6), $W$ is the FWHM of the higher order function, FWHM is the full width at half maximum, $m$ is the order of higher Gaussian function and $L$ is the length of grating. Typical values for designing of SGFBG1 are grating period is 532.617 nm, length of grating is 5 cm, apodization is super Gaussian, periodicity of chirp is linear, chirp parameter is $25 \times 10^{-9}$ m$^2$, number of segments is 801, Index modulation $0.6 \times 10^{-9}$ m$^2$, grating shape is sinusoidal. After proper designing, fabrication, and testing of respective apodized chirped FBG, the next stage is to design PAA while keeping in mind the various parameters such as reflection coefficient, Voltage standing wave ratio (VSWR), and radiation pattern and so on. Now, in the coming subsection, discussion is focussed on details of various parameters used for fabrication of photonically fed antenna array.

### 3.2 Fabrication of phased array antenna

A rectangular microstrip antenna has been designed, simulated and fabricated at Ku-band. The operating frequency is 13 GHz. An array of the uniformly spaced antenna element is designed using eight microstrip patch antenna [21]. Each element of the array antenna is individually excited using coaxial feeding technique as shown in Figure 5.

Microstrip antenna consists of a thin metallic rectangular patch photo etched on the top side of the substrate (dielectric) having a fully conducting metallic ground plane below it. FR4 with dielectric constant $\varepsilon_r = 4.4$, loss tangent ($\tan \delta$) equal to 0.02 and thickness of 1.6 mm is used as substrate [21]. This antenna is simulated in high frequency structure simulator 3D electromagnetic computation tool and the necessary characteristics are mentioned in terms of return loss, VSWR, peak gain and radiation patterns. The performance of the microstrip antenna depends on its dimension, the operating frequency, radiation efficiency, directivity, return loss and other related parameters. For an efficient radiation, following equations are valid.
used for calculations. Practical width of patch is calculated using the following equation [23]:

$$W = \frac{1}{2f_r \sqrt{\varepsilon_0 \mu_0}} \sqrt{\frac{2}{\varepsilon_r + 1}}$$ (7)

The effective dielectric constant, $\varepsilon_{eff}$ is given:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + \frac{12b^2}{w^2} \right]^{-\frac{1}{2}}$$ (8)

where $\varepsilon_r$ is the dielectric constant of material, $w$ is the width of patch and $b$ is the height of substrate. Prolonged electrical length, $\Delta L$ of the patch due to fringing effect can be calculated using [23]:

$$\Delta L = \frac{0.412(\varepsilon_{eff} + 0.3)(\frac{w}{b} + 0.264)b}{(\varepsilon_{eff} - 0.258)(\frac{w}{b} + 0.8)}$$ (9)

The effective length, $L_{eff}$ is given by:

$$L_{eff} = \frac{\varepsilon_{eff} \lambda}{2f_r \sqrt{\varepsilon_{eff}}} - 2\Delta L$$ (10)

| Design parameters       | Value  |
|-------------------------|--------|
| Operating frequency     | 13 GHz |
| Dielectric constant     | 4.4    |
| Substrate thickness     | 1.6 mm |
| Substrate width         | 19 mm  |
| Substrate length        | 23 mm  |
| Patch length             | 9.3 mm |
| Patch width              | 6.2 mm |
| Radius of coax pin       | 0.2 mm |

**Table 1** Dimension of fabricated antenna

Detailed description of antenna parameters are given in Table 1.

## 4 EXPERIMENTAL SETUP

Lightwave from tunable laser, as shown in Figure 6, is intensity-modulated by microwave signal of 13 GHz coming from RF generator, when passes through LiNbO$_3$ Mach–Zehnder modulator. The modulated optical signal is then split equally into eight arms by 1 × 8 optical splitter and each arm consists of circulator and super-Gaussian apodized linearly chirped FBG of different length and chirp parameter as a TTD module. The lightwave whose wavelength matches the chirped grating period will be reflected and reaches the photoreceiver through circulator. In the proposed setup, the different reflection wavelengths of the chirped FBG are controlled within the tuning capability of the laser source $\Delta \lambda$ at the time of fabrication. Optical signal obtained at the output of each circulator is time delayed signal having linear delay progression which arises due to the group delay of respective grating. In TTD unit, the point at which intensity-modulated lightwaves are reflected after travelling the same distance from the input of grating is denoted by centre wavelength $\lambda_C$. When the wavelength of light emitted from the tunable laser source is tuned to $\lambda_C$ then we will get a zero time delay progression, resulting in a 0° steering angle. Thus, to steer a far-field radiation pattern of phased array antenna, one has to tune the laser output either at $\lambda_1$ or $\lambda_2$, that is, wavelength other than center wavelength within the spectral width of grating. The time delay of the microwave signal depends on the locations from which the light is reflected at the gratings, and we can control it by tuning the wavelength of the optical carrier. To get a high signal-to-noise ratio at the output of photoreceiver, an EDFA is inserted just before the optical splitter to overcome the insertion loss.

The bandpass filter (BPF) is used to filter the unwanted chirping phenomena that get superimposed on the intensity-modulated lightwave, as can be seen in Figure 10, there is sudden spikes at 150 ps for 1550 nm, which further filters out when passes through BPF, as shown in Figure 11.

**Figure 6** Experimental measurements done inside the anechoic chamber for time-delay measurements containing TTD module for 13 GHz PAAs. EDFA, Erbium-doped fiber amplifier; PD, photodetector; SGFBG: Super-Gaussian apodized chirped fiber Bragg grating; TTD, true-time delay.
5 | RESULT AND DISCUSSION

Figure 7 shows the simulated delay versus wavelength graph for LCFBG1 and SGFBG1. The calculated value of ripples for 3-dB reflection bandwidth in LCFBG1 and SGFBG1 are 5.098 and 0.390 ps. Higher the ripples more will be fluctuation in delay selection at particular wavelength, which leads to inaccurate beamforming at particular angle. Figure 8 shows the experimental and simulated result of reflection spectrum of SGFBG1 (value of parameters are given in Section 3.1)). Result clearly indicates that FBG is properly designed and fabricated. Now, the theoretically and experimentally calculated values of delay provided to modulated optical signal are shown in Figure 9. The deviation in simulated and experimental result for SGFBG1 to SGFBG3 is attributed to human error while fabricating the FBG with desired specifications. After considering Equation (4) and Figure 9, the maximum value of time difference between the adjacent antenna elements is 36, 35.84, 35.9, 36.04, 35.96, 36.002, and 35.79 ps. All these values are approximately equal to each other, so designed FBG satisfies the requirements of Equation (4). When the laser wavelength is tuned to 1542 nm, the resultant delay difference introduced into the optical signal while passing through the SGFBG8 is 36 ps.

In Figure 10, we have considered 150 ps as the observation point, that is three cycles are completed up to 150 ps. At the centre wavelength of all our fabricated SGFBG is 1550 nm, so
0 ps of delay should be introduced in the lightwave moving into the respective Bragg grating. Figure 10(b) depicted the experimentally obtained output of PD feeded by the signal reflected from SGFBG8, which clearly shows the introduction of 0 ps of delay in modulated lightwave, since three cycles are covered till 150 ps.

Figure 10(b), also shows that when laser wavelength is tuned to 1542 nm, then 36 ps of delay is introduced into the microwave signal feeded to the antenna. The spikes that is obtained at 150 ps is due to the chirping nature of SGFBG which get superimposed on the modulated optical wave which get reflected after travelling into it. This sudden spikes can be easily removed by passing the output of PD through a bandpass filter (as shown in Figure 11) before amplifying the microwave signal feeded to the respective antenna unit.

With the help of Agilent vector network analyzer (VNA), reflection coefficient is measured, while with the help of anechoic chamber gain and radiation pattern are obtained. Figure 12 depicts the comparison of simulated and measured return loss or reflection coefficient. The fabricated prototype of proposed eight-element PAA is tested under VNA for the S-parameter measurement practically. The simulated and experimentally obtained return loss characteristics have presented in Figure 12, shows a good agreement with each other. According to observation, the experimental reading shows return loss is $-13.8$ dB at 13.0 GHz while simulated results is $-19.1$ dB at 13.05 GHz.

The radiation characteristic of proposed antenna is measured at the far-field region, that is, $R = \frac{2D^2}{\lambda}$, where $D$ is the
largest dimension of designed antenna and $\lambda$ is the wavelength with respect to the operating frequency, that is, $f = 13$ GHz. From the far-field radiation pattern, we can observe the directional properties of the proposed antenna. It has been observed that a good sidelobe level and 3-dB beamwidth observed at central frequency. The antenna show main lobe direction at $\pm 20.07^\circ$ (shown in Figure 13), 41.3$^\circ$ (shown in Figure 14), 61.4$^\circ$ (shown in Figure 15), 69.3$^\circ$ (shown in Figure 16) and angular width of 21$^\circ$ at 13 GHz in $E$-plane ($y$-plane). To steer the main beam from 20.07$^\circ$ to 41.3$^\circ$, different delay is provided that depend on the grating length and chirp parameter of apodized FBG.

6 | CONCLUSION

This study demonstrated that SGFBG can be utilized as variable TTD lines for phased array antennas. The main advantage of this element lies in its ability to produce continuous steering of the array scan angle by tuning the wavelength of the optical carrier. Here, we provided a step-by-step theory assisted by simulative and experimental outcomes of photonic TTD module requirement for phased array antennas. For a 13 GHz PAA, a very close similarity was reached between the experimental and calculated time delay difference of a TTD module, which offers a beam steering in the required direction of 0$^\circ$ and
±69°. Chirped grating-based implementation of TTD unit offers greater flexibility and more beamforming capabilities. In addition to broadband radio astronomy aperture arrays, another highly demanding application of optical beam steering is satellite communication. Such a setup can be introduced in planar integrated optical waveguides to take advantage of the benefits of waveguides over optical fibre, such as enhanced stability with regard to environmental modifications such as temperature and vibration and a smaller general size [9].

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