Microwave Waveform Generation with High Chirp Rate and Central Frequency using Dual-Parallel Mach-Zehnder Modulator for an Efficient Microwave Beam Steering Network

Nimish Kumar Srivastava[1], Akash Srivastava, Sanjeev Kumar Raghuwanshi

Abstract – **Photonic generation of a linearly chirped microwave waveform (LC-MW) with high chirp rate and central frequency using Dual Parallel Mach-Zehnder Modulator (DP-MZM) is proposed. Many schemes are active today to generate the chirp microwave signals where optical frequency to time mapping is most commonly used technique. In the proposed scheme a modulated chirp waveform is applied at the RF port of one MZM1 of the DP-MZM and another MZM2 RF port is feed by microwave carrier. A chirp microwave waveform with high central frequency and very high time bandwidth product is generated. In microwave pulse compression a linearly chirped microwave with central frequency up to tens or even hundreds and bandwidth of few GHz are often needed, in order to meet the requirement of application in Radar system to increase the Doppler range resolution. In this paper central frequency of 6 GHz, 3 dB bandwidth of 13 GHz, chirp rate of 0.09619×10^{18} Hz/sec and time bandwidth product of 1756 has been achieved. The main attraction of this paper lies in the technique called photonic true time delay module based on discrete fiber Bragg grating for efficiently generating and steering the microwave beam in a desired angle.**

Keywords – **Doppler Range Resolution, Dual Mach Zehnder Modulator, Chirp Rate, True Time Delay, Chirped Fiber Bragg Grating.**

I. Introduction

In the new era of remote sensing a microwave pulse compression is frequently used for remote sensing application where a long microwave waveforms are transmitted and receiver compressed it to increase the range resolution. The range resolution is the minimum separation in range of two targets of equal cross section that can be resolved as separate targets. When a target is moving relatively to Radar the central frequency of returned pulses must be different from that of incident pulse. A short pulse exhibit better range resolution but it tends to reduce average transmitted power that leads to reduce Radar range. In order to get average transmitted power, better range resolution and SNR value of short pulse the signal must be frequency or phase modulated. This process is adopted as pulse compression. It is observed that two objects which are very close to each other need to be separated by at least $\frac{\tau_p}{2}$ order to get two distinct echo signals through Radar [1-3] Hence Radar Range resolution ΔR be calculated through [4] $\Delta R = \frac{c.\tau_p}{2} = \frac{c}{2.B}$, where $B = \frac{1}{\tau_p}$, τ_p = pulse width, C= light velocity, B= signal bandwidth. As short pulse exhibit better range resolution so to achieve high pulse compression ratio radar pulses are generally chirped. The chirp signal is usually a sinusoidal signal whose frequency increases or decreases with respect to time. In microwave pulse compression technique it should be needed that the time bandwidth product must be large in order to 10^2 or 10^3 [4]. Such type of linearly chirped microwave waveform (LCMW) in electrical domain can be possible by using voltage controlled oscillator (VCO) or DSP module. Although various novel and appreciable work has been done from initial time in this field like in paper [5] author highlighted the effect of range-Doppler coupling on accuracy of target tracking in chirp Radar. They demonstrated their work through various numerical examples. In the paper [6], the work is focused on the generation of linearly chirped microwave waveform by using spectral shaping and wavelength to time mapping. But limitation is of central frequency and bandwidth, so in the result limited central bandwidth of LCMW to few GHz is obtained. Because in RADAR application central frequency required up to tens or even hundred and bandwidth of a few GHz are often needed. So the key advantage of using photonic techniques for LCMW generation is high frequency and broad bandwidth which is not possible in electronic devices, thanks to modern photonics to offer us such facilities. In this paper we have proposed a photonic approach to generate a LCMW using a single Dual Parallel Mach Zehnder Modulator (DP-MZM). A DP-MZM has a Mach Zehnder Interferometer (MZI) type structure with one MZM1 incorporated in upper arm and second MZM2 in the lower arm. A microwave carrier signal applied at the RF port of MZM1 and a chirp waveform (generated experimentally) is applied at the RF port of MZM2. In case of

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high speed communication (10 GBPS and beyond it) it becomes extremely difficult to modulate the optical wave generated from any light source directly therefore external optical modulators [7] are used. The signal after modulation via both of the MZMs are combined through 50:50 combiners and then applied to photo detector for optoelectronic conversion. The key advantage of this proposal is to generate high quality optical mm wave. The scheme used in this paper is more advanced than previous published work (D. Zhu and J. Yao "Dual-Chirp Microwave Waveform Generation Using a Dual-Parallel Mach–Zehnder Modulator) [8-10] in terms of bandwidth, central frequency and chirp rate respectively. Furthermore, after generating chirped microwave waveform the focus of this paper shifted to incorporate a true time delay module which will utilize the generated chirped waveform and provide a sufficient time delay based on the successive spacing between spatially distributed discrete fiber Bragg grating. Thus, the beam pointing angle of the broadside far-field radiation pattern of phased array antenna (PAA) can be controlled by the grating location difference between adjacent delay lines with respect to the wavelength from λ_C to $\lambda_C + \Delta\lambda$.

II. Principle and Specific Parameters of Each Component

A complete schematic block diagram of the proposed linearly chirped microwave waveform (LCMW) generation based on single DPMZM is given in the Fig. 1. An unmodulated continuous light wave (expressed as $E_0 \cos(\omega_0 t)$, where E_0 the amplitude of optical field and ω_0 the angular frequency of optical carrier) sent over DP-MZM via polarization controller (polarization controller is used before MZM to minimize the polarization dependent loss). The DP-MZM consist of two MZMs (MZM1 and MZM 2) one in upper arm and another in Lower arm of DP-MZM. A phase modulator is also incorporated here at lower arm after MZM2 to control the phase of the optical wave. An electrical signal applied at the RF port of MZM 1 and an arbitrary chirp microwave waveform (generated experimentally) is applied at the RF port of MZM2. The applied chirp signal has the chirp rate of $1.5\times10^{18}\,\mathrm{sec}^{-2}$. The schematic model consists of one non return to zero pulse generator followed by a user defined bit sequence generator. The NRZ pulse generator [11] converts the input binary signal into a non –return to zero coding format. It shapes the input digital signal to a Not Return to Zero electrical signal. The output of the NRZ-PG is given to a low pass Bessel filter which provides a maximally flat group delay or propagation delay across the frequency spectrum. In this paper we have used $LiNbO_3$ MZM [12] throughout because it provides low loss and large extinction ratio.

The chirping in $LiNbO_3$ MZM is mainly due to imbalance between the modulation depths in the two arms of Mach Zehnder waveguide.

A. Chirp Signal Generation Experientially to Feed at the RF Port Of MZM-2

Simulation setup parameter and specification of devices used for the generation of chirp signal are given in the Table 1.

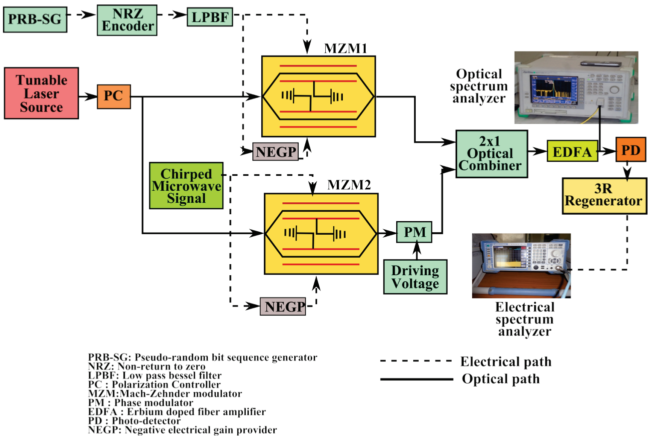

Fig. 1. Schematic diagram of proposed chirped microwave waveform generation system

TABLE 1
SIMULATION SETUP PARAMETER AND SPECIFICATION OF DEVICES USEFUL FOR THE GENERATION OF CHIRP SIGNAL TO EXPERIMENTALLY

Devices	Parameter	Value
Continuous wave laser	Frequency	193.1THz
	Power	10 dBm
	Line-width	10 MHz
Single mode fiber	Reference wavelength	1550 nm
	Length	3 km
	Dispersion	17 ps/nm/km
Mach-Zehnder Modulator	Extinction ratio	20 dB
	Operating wavelength	1550 nm
	Bias voltage (DC)	6 V
	MZM switching voltage (V_π)	4 V
	Modulation voltage	1.5 V
Fiber Bragg Grating	Chirp function	Linear
	Wavelength	1550 nm
	Length	6 mm
	Effective index	1.45
Photo-detector	Responsivity	1 A/W
	Dark current	10 nA
Erbium doped fiber amplifier	Core radius	2.2 µm
	Er doping radius	2.2 µm
	Er metastable lifetime	10 ms
	Numerical aperture	0.24
	Er ion density	$1\times10^{25}/\mathrm{m}^3$
	Pump wavelength	980 nm

According to the experimental parameters given in Table 1 we have followed the schematic block diagram given in the Fig. 2 for chirp signal generation.

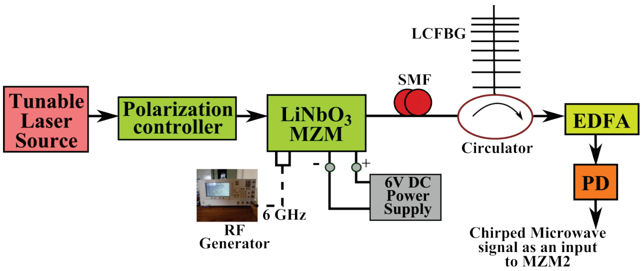

Fig. 2. Schematic diagram of generation of chirp arbitrary microwave waveform generation as an input to MZM2

In the proposed model a continuous wave light from a tunable laser (OSICS ECL 1560 Tunable Laser Module) having optical power of 10 dBm at 1550 nm central wavelength is used. A 6 GHz microwave signal through RF generator (Agilent technologies E8257D having full frequency span range of 250 kHz–20 GHz) is given to RF port of MZM (MXAN-LN-40 Photline). A 6V DC voltage is provided to bias the MZM. The frequency modulated output from MZM is given to a 1st port of optical circulator via 3 Km single mode fiber. The signal is now circulated to 2nd port of circulator where a 1550 nm linearly chirp fiber Bragg grating has been introduced. The LCFBG reflect the 1550 nm central wavelength optical carrier hence this will work as a splice filter [13]. The optical signal analysis carried out by optical spectrum analyzer (ANRITSU MS9710B). The signal is detected by PD (Optilab-40GHz) which converts the signal from optical to electrical domain. The electrical signal is analyzed by electrical spectrum analyzer (ROHDE & SCHWARZ-FSL-18) useful in calculating and displaying the signal intensity, power spectral density and phase of the electrical signal in frequency domain. In our experimental setup, ITUs G.655has been used as a single mode fiber. Analysis of the impact of fiber dispersion on optical mm-wave generation has been done by using opti-system simulator. We have got the high time-bandwidth product of 1756 through this experimental setup. We have deliberately chosen the same simulation parameter in our opti-system model as we are going to do an experimental setup for better comparison of results.

The signal lies in C band (1530 to 1560 nm), to amplify it we have used a EDFA. The optical amplifier increases the power level of incident light through stimulated emission. The real experimental setup to generate the chirp microwave signal to drive the MZM2 is given in Fig. 2.

B. Experimental Setup

As in previous section the generated chirp signal is sent over the RF port of MZM2 of DP-MZM. The combined signal from MZM1 and MZM2 and then applied to the photo-detector for optoelectronic conversion. In comparison with single electrode MZM dual electrode is more flexible because the amplitude and phase of two electrodes can be adjusted to realize, that's why the author have chosen dual port MZM for MZM1 and MZM2. Intrinsic chirp parameter [14-15] is independent of amplitude of electric drive signal and it's given by

$$\alpha = \frac{V_1 + V_2}{V_1 - V_2}. \tag{1}$$

Fig. 3. Experimental setup as per the proposed model in Fig. 1.

where V_1 and V_2 is bias voltage of MZM port. Three cases can be consider here:

1. If $V_1 = V_2$ then $\alpha = \infty$ that is the condition of pure phase modulation.
2. If $V_1 = -V_2$ then $\alpha = 0$ pure intensity modulation.
3. If $\alpha = 0$ then electrical signal is given to only one arm of MZM and hence modulation takes place only one arm.

The condition mentioned in case 2 is called as push pull condition (i.e. is the condition for chirp free pure intensity modulation) where [$V_{bias1} = -V_{bias2} = \frac{V_\pi}{2}$] the phase shift are equal in magnitude but opposite in sign. The phase shift experienced by the two arms depends on voltage applied to upper and lower arm of MZM.

In the principle block diagram as given in Fig. 1 to generate the LCMW using DP-MZM we have used parameters given in the Table 2.

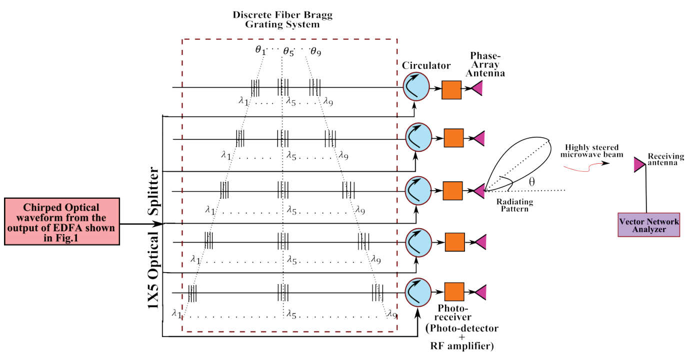

Fig. 4. Experimental setup for beamsteering with the help of discrete fiber Bragg grating system

TABLE 2
PARAMETERS SPECIFICATION OF THE COMPONENTS USED IN THE PRINCIPLE MODEL BASED ON DP-MZM

Devices	Parameter	Value
Continuous wave laser	Frequency	193.1 THz
	Power	5 dBm
	Line-width	10 MHz
	Optical power	10 dBm
MZM1	Extinction ratio	20 dB
	Operating wavelength	1550 nm
	Bias voltage	9.5 V
	Bias voltage	-8.5 V
	Modulation voltage	1.5 V
	MZM switching voltage (V_π)	4.0 V
MZM2	Extinction ratio	20 dB
	Operating wavelength	1550 nm
	Bias voltage.1	7.5 V
	Bias voltage.2	-6.5 V
	Modulation voltage	1.5
	MZM switching voltage (V_π)	4 V
Phase modulator	Phase deviation	90 Degree
	Driving electrical power	10 dBm
Photo detector	Responsivity	1 A/W
	Dark current	10 nm
Optical spectrum analyzer	Wavelength range	600 to 1750 nm
Electrical spectrum analyzer	Frequency range	9 kHz to 18 GHz
	Signal analysis bandwidth	13 MHz

The generalized array factor of N-element PAAs can be written in normalized form as [11-14]:

$$(\text{A.F.})_N \cong \left[\frac{\sin(\frac{N.\psi}{2})}{N.\sin(\frac{\psi}{2})} \right], \quad (2)$$

where $\psi = k.d_p.\sin(\theta) + \beta$, $k = \frac{2\pi}{\lambda}$, k is the spatial angular frequency of the wave, λ is free space wavelength. $\beta = \frac{(-2.\pi.n_{eff}.2.\Delta d)}{\lambda_{min}}$, called as progressive phase factor, λ_{min} is the microwave wavelength corresponding to highest frequency, θ is the scan angle relative to broadside direction, Δd is the incremental spacing required between each grating, and d_p is the spacing between each antenna element. In order to get maximum value of radiation pattern of antenna we take $\psi = 0$ in Eq. 2, as a result of this

$$d_p.\sin\theta_{max} = 2.n_{eff}.\Delta d \Rightarrow \sin\theta_{max} = 2.n_{eff}.\frac{\Delta d}{d_p}. \quad (3)$$

Above equation, highlights that the beam-steering direction is obtained by progressive spacing between grating and is not dependent on the microwave frequency. In our, experimental setup the photonic true time delay module comprises of spatially distributed array of 9 FBGs. The peak-reflection wavelength of different FBGs are within the tuning range of the laser source, i.e., $\Delta\lambda$. The center reflection wavelengths of the gratings in each delay line from left to right are 1545.7, 1546.8, 1548, 1549.5, 1551.3, 1553, 1554.6, 1555.7 and 1556.6. In Fig. 4, all the FBG along the same dashed lines are designed with the same central reflection wavelengths. With the help of tunable laser source, one can tune its output wavelength with the central reflection wavelength of the FBGs along the dashed lines, results in different radiation directions due to different time delay progressions, which ultimately produces beam-scanning of the phase array antenna.

III. RESULTS AND DISCUSSION

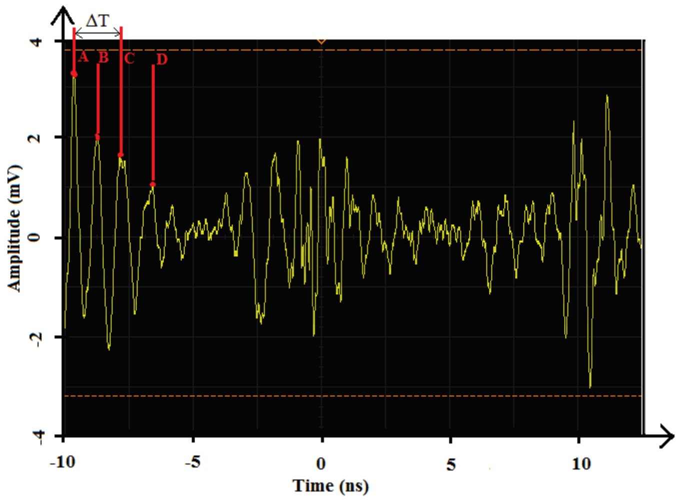

Fig. 5. Digital Storage Oscilloscope (experimentally) output of generated chirped microwave waveform due to continuous wave laser

The experimental results based on setup given in Fig. 1 discussed one by one in the coming part of this section. The experimental setup for the generation of chirp microwave arbitrary waveform is similar to Fig. 1. An electric signal having the power of 10-dBm is given to RF port of MZM1- On the other hand, MZM2 is feed by a chirp signal (mentioned in above section 2) having the chirp rate of $1.5\times10^{18}\ \text{Hz}/\text{sec}$ .The intensity modulated output from MZM1and MZM2 is combined by optical power combiner who sends to photo detector via EDFA for Opto-electronic conversion. The chirped microwave signal of very high TBWP is obtained at the output of PD is further analysed by using Digital spectrum oscilloscope. With the help of markers we have marked the point of two arbitrary consecutive pairs of peaks A, B and C, D. Value of all arbitrary chosen points are given below:

$T_A = -9.8 \times 10^{-9}$ sec

$T_B = -8.7 \times 10^{-9}$ sec

$T_C = -7.7 \times 10^{-9}$ sec

$T_D = -6.8 \times 10^{-9}$ sec

$T' = T_A - T_B = -1.1 \times 10^{-9}, T'' = T_C - T_D = -0.9 \times 10^{-9}$

$$f_a - f_b = \frac{1}{T'} - \frac{1}{T''} = 0.202 \times 10^9 \text{ Hz}$$

$\Delta T = T_A - T_C = -2.1 \times 10^{-9}$ sec

$$\text{Chirp rate} = \left| \frac{f_a - f_b}{\Delta T} \right| = 0.09619 \times 10^{18} \text{ Hz/sec}$$

Now, in order to calculate time-bandwidth product (TBWP) we use the formula [15-16]: $\text{TBWP} = \frac{(\text{Bandwidth})^2}{\text{Chirp rate}}$.

In our experimental analysis, the generated chirped microwave waveform has a 3 dB bandwidth of 13 GHz.

$$\therefore \text{TBWP} = \frac{(13 \times 10^9)^2}{(.09619 \times 10^{18})} = 1756.$$

According to the experimental results, a time bandwidth product (TBWP) of 1756 is achieved for the generated waveform. The central frequency of the generated microwave waveform is about 6 GHz. After successful generation of very high TBWP, the next part of the experimental analysis comprises of steering of broadside direction of PAA based on variation in incremental spacing between successive fiber Bragg grating system. Fig. 6 shows that for microwave frequency of 6 GHz along with the spacing between each an every element of antenna $d_p = 23\text{mm}$, the different beam steering angle are -60^0, -47.97^0, -31.80^0, -15.60^0, 0^0, 19.79^0, 34.20^0, 55.79^0 and 69.59^0. The incremental spacing required between each grating that results in different directional angle of far field radiation pattern of phased array antenna has been mentioned in Table 3.

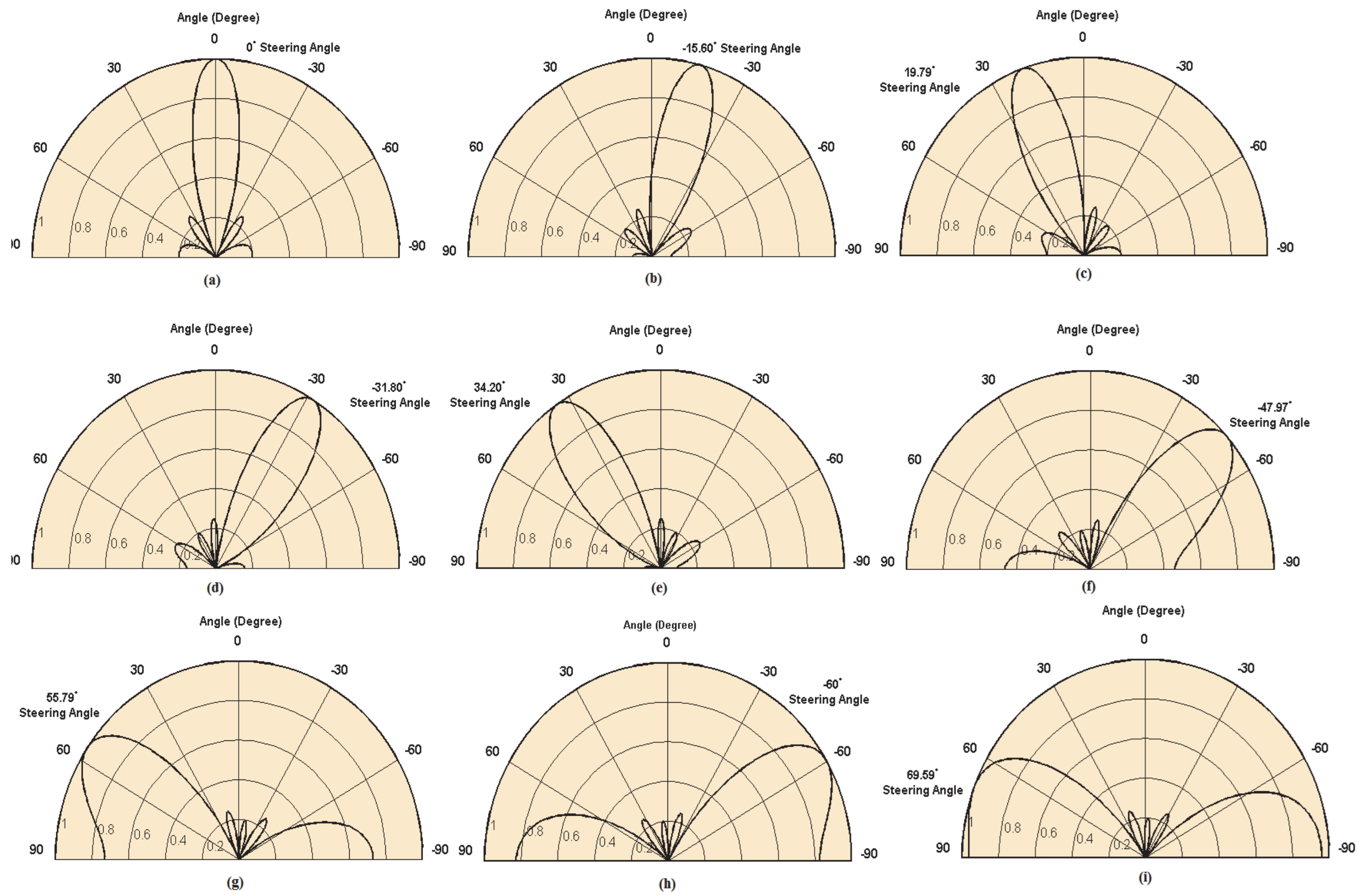

Fig. 6. Far field radiation pattern of 5-element PAA showing the beamsteering at frequency of 6 GHz with the help of true time delay module

TABLE 3

CALCULATED TIME DELAYS OF DELAY LINE 2 AT MICROWAVE FREQUENCY OF 6 GHZ

Grating	Grating spacing (mm)	Theoretical time delay (ps)	Experimental time delay (ps)	Steering angle (Degree)
L1	-7.2	-72	-70	-60
L2	-6.6	-66	-58	-47.97
L3	-4.4	-44	-40	-31.80
L4	-2.2	-22	-19	-15.60
L5	0	0	0	0
L6	2.8	28	27	19.79
L7	4.7	47	42	34.20
L8	6.9	69	64	55.79
L9	7.8	78	73	69.59

IV. CONCLUSION

We have demonstrated a model based on dual parallel Mach Zehnder Modulator. At the end of this paper we have concluded various outcomes from the simulated experimental setup like gain from input to output at 193.1 THz CW laser frequency is 6.442dB, electrical power at the output is 5.771 dBm. We have estimated the various parameters of chirp microwave waveform like central frequency of 6 GHz, 3dB bandwidth of 13 GHz and TBWP as 1756 which is highly beneficial for increasing range resolution of RADAR. The generated Chirp microwave waveform is widely useful in modern Radar system in which long microwave waveforms are transmitted and then received and compressed at Radar receiver to increase the range resolution and detection distance. In telecommunications, medical healthcare, physical chemistry imaging, and sensing systems chirp waveform is extremely applicable now a day's. Furthermore, in this paper we have proposed and demonstrated a true time delay module for wideband phased array beam-steering of phased array antenna. The most attractive point of the proposed technique lies in its ability to produce continuous scanning of phased array antennas broadside direction by tuning the wavelength of the optical carrier.

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