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Design and Analysis of Impulse Radio (IR) Based UWB Transmitter with Antenna

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ABSTRACT

The use of ultra-wideband (UWB) in target detection, radar and wireless connectivity, specifically in the medical world, has attracted a lot of attention. The concept that the IR-UWB system does not necessarily require carrier signals is one of its most appealing features. IR-UWB can transmit information using short Gaussian monocycle pulses. In light of these advantages, this paper proposes a novel UWB transmitter system which consists of UWB signal generating circuits and UWB antenna, which work together to create entire UWB transmitter. It is based on impulses and has a simple architecture with low power consumption. The proposed transmitter is realized in Cadence tools with 90nm CMOS technology and proposed UWB antenna is simulated using Advanced Design System (ADS) simulator software. In addition, the transmitter circuit and the antenna are co-simulated using ADS software. The illustrated UWB transmitter uses a low-power supply and generates $\mathbf{359.44}\boldsymbol{mV}$ pulse amplitude with pulse duration of $\mathbf{100}\ \boldsymbol{ps}$ for the Gaussian monocycle pulse. Due to its increased output voltage swing and reduced power consumption when comparing to other circuits, the proposed architecture is functional and suitable for use in short-range wireless networks and medical applications.

1. INTRODUCTION

Ultra-wideband (UWB) radio technology is highly applied in radar, detection and defense related applications throughout the previous few decades. Since February 2002, when the FCC approved the use of UWB for information transmission and the medical sector (Huo *et al.*, 2017a), much research has been conducted. Subsequently, this communication technology has advanced rapidly in applications demanding high speed wireless communication. UWB radio technology in imaging systems is ideal for medical devices since it allows a doctor to observe the inside status of human anatomy where no surgical process is mandatory. Whereas X-ray and ultrasound require direct touch, UWB devices can operate from a distance (Neto *et al.*, 2015). Basic logic gates are used to develop IR-based UWB transmitters. Additional circuits, like phase locked and delay-locked loops for clock and data synchronization can be included in medical devices and wireless communication design. In medical applications, short pulses generated by UWB technology is sent inside the human body and scattered signals from different organ parts are accumulated and analyzed based on the received signals. This technology reduces the need for clock synchronization and simplifies the circuitry. Numerous studies have been carried out to comprehend many features of UWB transmitter, hence facilitating newer circuit with enhanced performance parameters. However, there were more scopes to improve the performance of UWB transmitter. Some recent research (Lo *et al.*, 2013; Radic *et al.*, 2020; Bahrami *et al.*, 2015; Notch *et al.*, 2013) have designed UWB transmitter. The mentioned works has reduced the power consumption but there is huge scope of reducing the power by using different components as power consumption is one of the most important parameters for wireless medical devices. Moreover, there is also area of improvement in pulse duration and pulse amplitude since this parameter will improve the transmitter performance in terms of precision ranging, data rate and proper diagnosis. With this improvement, circuit complexity needs to be reduced so that it will be more feasible for fabrication. The above researches also not suggested UWB antenna compatible to the proposed transmission system which is also very important part of UWB transmitter. Taking all these research gaps into considerations, a new transmitter is proposed in this work.

2. PROPOSED ULTRA-WIDEBAND TRANSMITTER

The design of UWB transmitters for communication networks has been the subject of numerous studies. These architectures considered power requirements and compactness, which are significant design concerns in communication and medical applications(Rezaei *et al.*, 2016). This research work proposes a new structure for UWB transmitter based on impulses that has most of the desired properties. UWB transmitters might employ the Gaussian monocycle pulse (GMP) generating approach to make the circuitry simple and minimize size of the circuit. The designed transmitter consumes very less power which is suitable for medical applications(Krasnov *et al.*, 2020), and moreover it does not require frequency retrieval at the output. Block diagram of the proposed transmitter with antenna is illustrated in Figure 1 where all the functional blocks are shown.

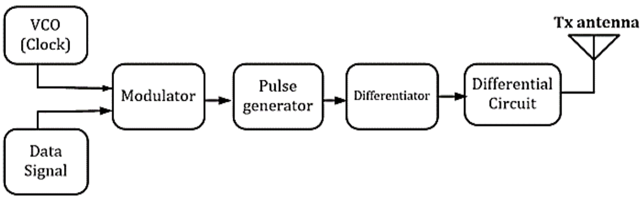

Figure 1: Block diagram of proposed IR-UWB transmitter with antenna

A. *Voltage Controlled Oscillator (VCO)*

The frequency of the generated signal by current starved voltage-controlled oscillator (CSVCO) is controlled by the input controlling voltage. The generated output voltage frequency can be adjusted over a wide range (Hz to GHz) by changing the regulating input(Aristov *et al.*, 2021). Another significant benefit of CSVCO is that the amplitude is maintained. Because of these benefits, a Current Starved VCO is employed in the proposed transmitter architecture, which consumes less power, has a wide range of oscillation frequencies and is simple to manufacture. The voltage-controlled oscillator included in this investigation contains three phases, as presented in Figure 2. Each delay inverter is formed by two MOSFETs (one N-channel and one P-channel), and other two function as current sources, limiting the amount of current flow through the inverter. For fluctuation of the regulating voltage from $300mV$ to $800mV$, the oscillating frequency varies from $1GHz$ to $10GHz$. The linearity of the circuit is affected by temperature.

B. *OOK Modulator*

When the signal is low, no carrier is sent in case of on-off keying (OOK) modulation scheme which is a basic modulation scheme for representing binary data (Hamza, 2016). For a given data rate, the signal bandwidth of a BPSK (Binary Phase Shift Keying) modulation and the signal bandwidth of an OOK modulation are the same. Furthermore, the modulator portion's digital logic circuit requires extremely little power. One of the inputs of the modulator is the clock signal generated from CSVCO and in another input binary data signal is given. If the information bit is one, this scheme delivers pulses; otherwise, no pulse is sent. The pulse frequency is determined by the clock input, and the total number of pulses is determined by the binary data signal.

C. *Gaussian Pulse generator, Differentiator and Differential Circuit*

Because they are affordable and simple to create, Gaussian pulses are used in short to medium communications networks. Despite the ease of the generating method, attaining pulse durations of a hundred picoseconds is tough. To generate a Gaussian pulse train either sine wave or square wave can be used (He & Zhang, 2010). In this work, a NOR gate is utilized to form a Gaussian pulse generator. OOK modulated clock signal is one of the two inputs of the NOR gates while the other is the inverted and lagged modulated clock signal(Belattar, 2018). To generate a negative Gaussian pulse, the positive Gaussian pulse is passed through an inverter(Fukuda *et al.*, 2015). These positive and negative Gaussian pulses are then differentiated using a differentiator circuit. In dual input balanced output differential amplifier circuit one input is the output of the differentiator and other input is grounded. Because of the differential form of output, the transmitter circuit is ideal for use with UWB antennas(Huo *et al.*, 2017b).The schematic diagram of transmitter circuit except antenna is shown in Figure 2.

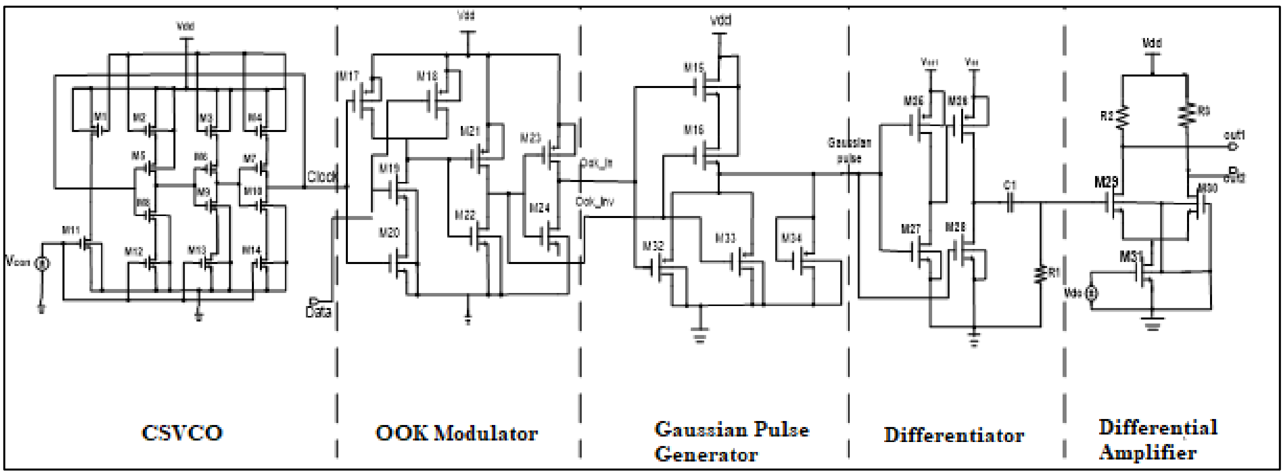

Figure 2: Architecture of proposed transmitter circuit

D. *UWB Antenna Design*

A simple coplanar wave guide (CPW) fed aperture antenna with UWB characteristics is designed and integrated with the proposed transmitter circuit. In (Li *et al.*, 2008), umbrella shaped antenna was proposed with bigger size. Using that concept, modifying ground plane and slotted radiation patch umbrella shaped antenna is introduced in this work. As a result, the overall size of the antenna reduced and radiation pattern and gain are also improved. Figure 3 depicts the suggested UWB antenna layout. The dimension of the antenna including ground plane corners is 32mmx28.5mm. A rectangular aperture cut out of the ground plane of a PCB and a CPW-fed umbrella-shaped radiation patch forms the antenna. The antenna is made on a moderate FR4 substrate with a dielectric constant of 4.3 and a thickness of 1.5 mm. The optimal dimensions of the various parts of the antenna are presented in Table 1. The end of the CPW feed line is attached to the semicircle endpoint of radius r1. The extrusion depth is 2mm of the umbrella-shaped patch and a semicircle slot is introduced onto the radiation patch to improve the bandwidth and gain of the designed antenna.

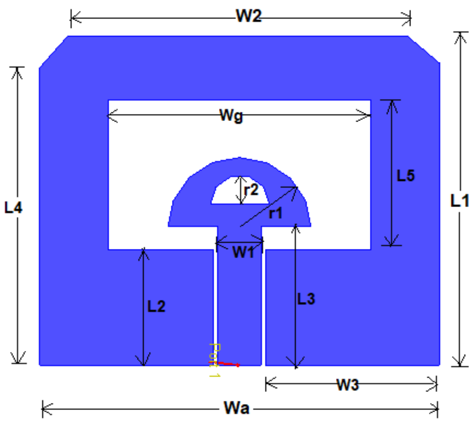

Figure 3: Geometry of the designed UWB antenna

Table 1
Antenna Dimensions, mm

L1	L2	L3	L4	L5	W1	d
28.5	10	12	26	13	3.6	1.9
W2	**W3**	**Wa**	**Wg**	**r 1**	**r 2**	**-**
28	14	32	22	6	2.3	-

A 50 Ω CPW transmission line powers the tiny rectangular aperture antenna (Gopi *et al.*, 2021).The umbrella-shaped patch is used in the designed antenna to improve the connectivity between the slot and the feed line, allowing the antenna to reach ultra-wideband performance(Li *et al.*, 2008). The upper two corner of the ground plane is modified (angular) which also improves antenna performance and reduces the size also (Bian & Che, 2008). The antenna returns loss bandwidth, radiation patterns, gain, group delay, and transmitted pulses waveform distortion were all calculated using Advanced Design System (ADS) software. The suggested antenna employs a CPW supplied technique to produce 50 $ohms$ input impedance.

E. *Integrating Proposed Transmitter Circuit and Antenna*

At first the transmitter circuit was implemented using Cadence virtuoso software and also the layout of the different parts of the circuit were generated by using the same software. Now to integrate the circuit of the transmitter with designed UWB antenna and to do EM/circuit co-simulation of transmitter circuit and UWB antenna, Advanced Design System (ADS) software is used(Hamza, 2016). The whole circuit having CSVCO, OOK modulator, Gaussian pulse generator, differentiator and differential amplifier was co-simulated with UWB antenna using ADS software but the last two functional blocks with antenna is shown in figure 4.

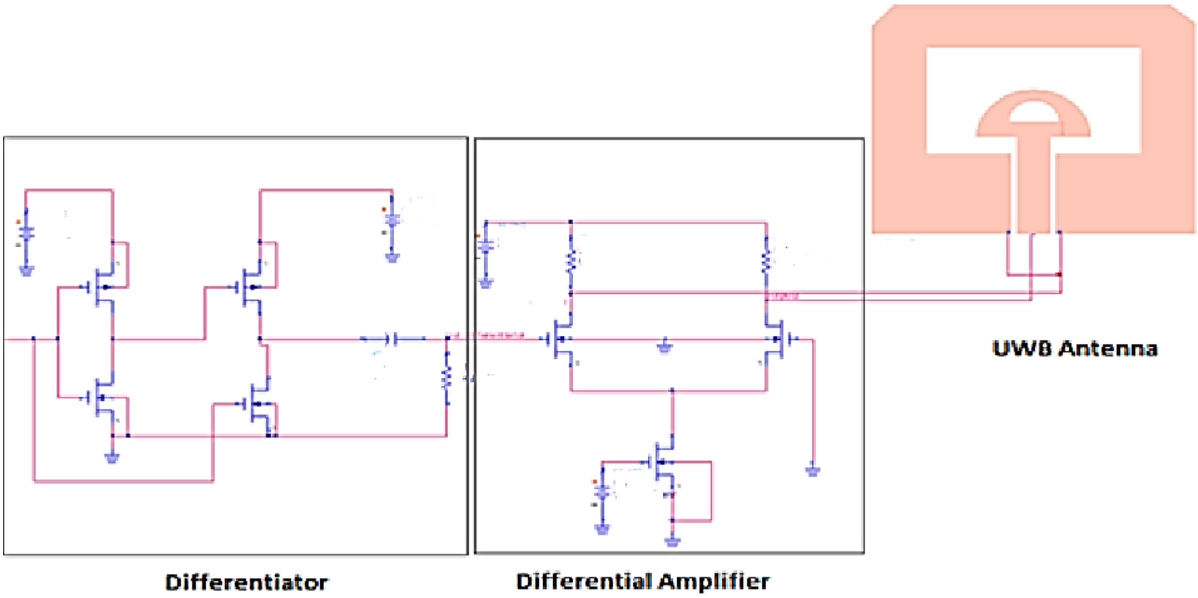

Figure 4: Schematic diagram representing integration of transmitter circuit with Antenna
(Last 2 blocks of transmitter circuit are shown with antenna)

3. RESULTS AND DISCUSSION

A. Simulated Results from Transmitter Schematic

The proposed transmitter circuitry, which was constructed using 90 nm CMOS process technology, was simulated using Cadence simulator tools. The proposed transmitter output waveforms are shown in Figure 5 at various stages. The pulse duration and pulse swing of the generated Gaussian mono pulse output are also determined from single GMP and bandwidth is determined from FFT of one GMP (Figures 6 and 7 respectively) (Ping, 2017).

From Figure 7 it is seen that the duration of pulse is $100ps$ and amplitude is $359.44mV$. Figure 6 shows the power spectral density of a single GMP, which gives a 10.6 GHz bandwidth at $-3dB$ point. Total calculated power consumption of the proposed architecture is 0.831 mW. The architecture of the pulse train also allows for higher maximum data rate while maintaining a narrow pulse width.

B. Simulated Result from Layout of Transmitter

Figures 8 to 12 show the layout of several blocks of the planned transmitter, which is implemented using Cadence tools and uses 90nm CMOS technology. The dimension of the CSVCO's is $12.64\mu m \times 16.73\mu m$, dimension of the modulator is $15.3\mu m \times 13.53\mu m$, the dimension of the Gaussian pulse generator is $10\mu m \times 15.61\mu m$, the dimension of the differentiator is $15.03\mu m \times 15.64\mu m$, and the differential amplifier measurement is $12.22\ \mu m \times 11.63\ \mu m$. The five blocks combined have a total dimension of $65.19\ \mu m \times 73.14\ \mu m$. Using a perfect sinusoidal input signal, the output characteristic curve of the schematic and layout are being examined. Only in differentiator circuit, a square wave was given as an input signal. Due to parasitic components, there is a slight discrepancy in the outputs between the schematic and the layout (Figures 13 to 17). With no errors, the layout passed the 90nm CMOS design rule check (DRC), as well as the LVS and RC checks, ensuring a successful design following fabrication.

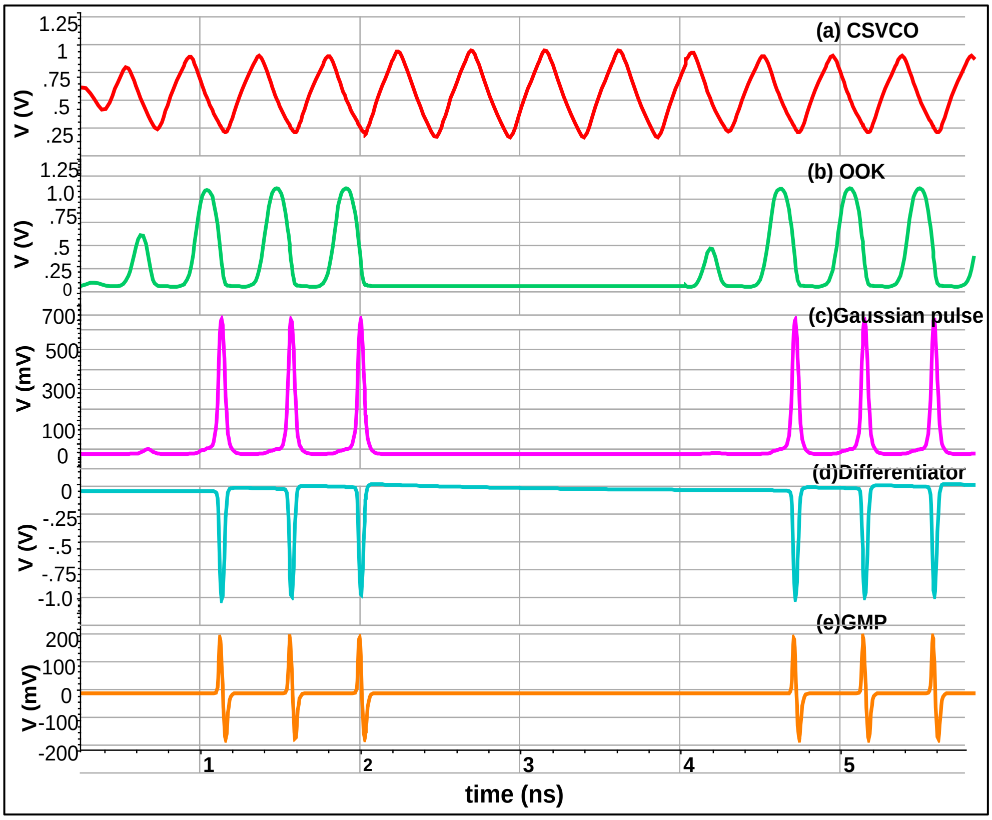

Figure 5: Output at different stages of proposed transmitter

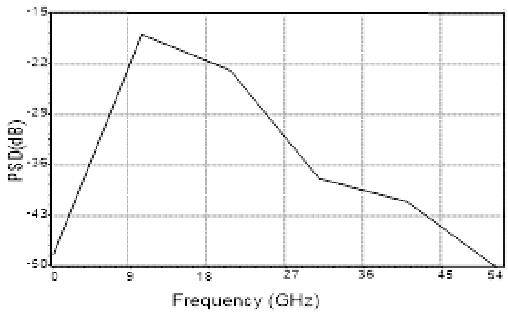

Figure 6: Power spectral density of single GMP

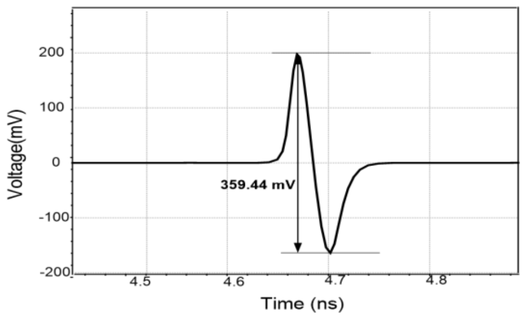

Figure 7: Gaussian monocycle pulse (single)

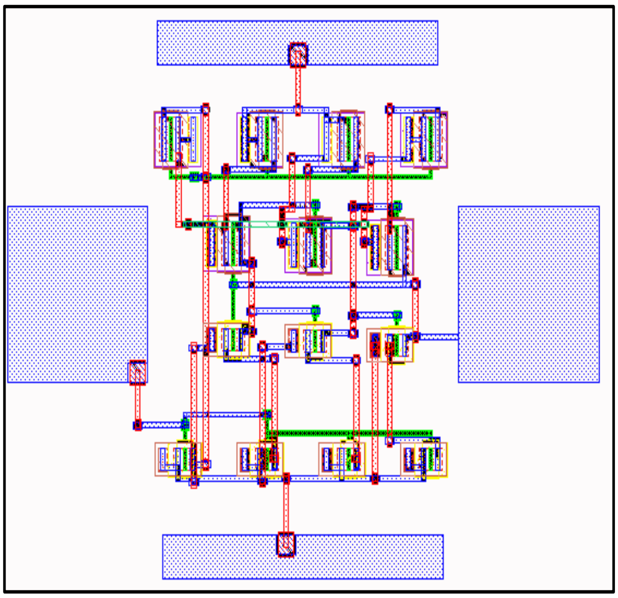

Figure 8: CSVCO layout

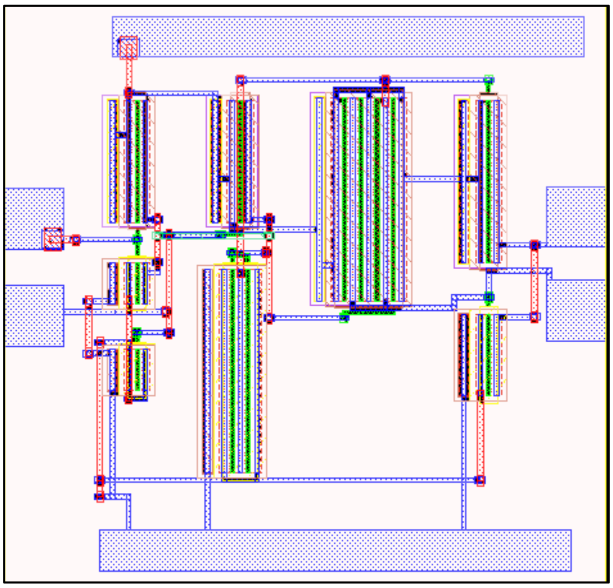

Figure 9: OOK modulator layout

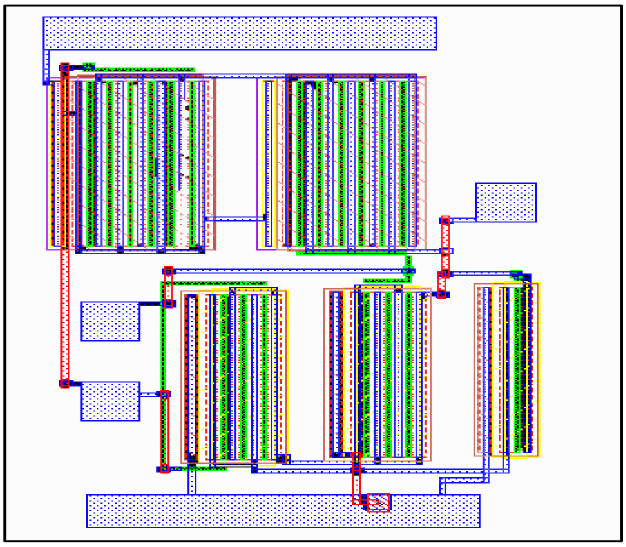

Figure 10: GP generator layout

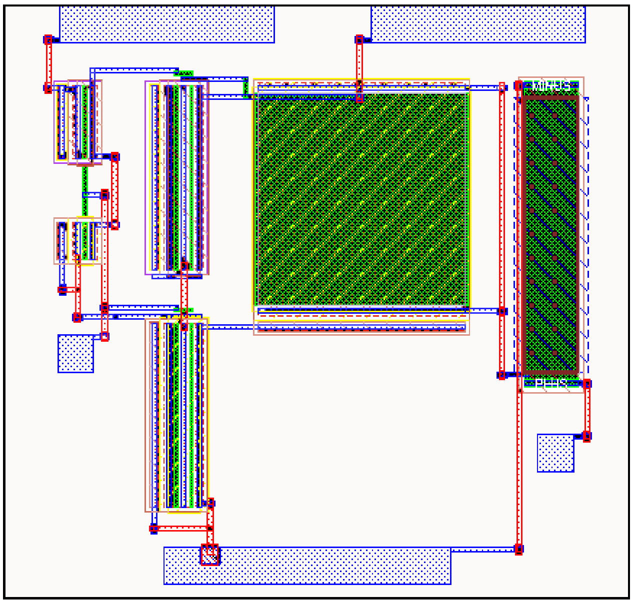

Figure 11: Differentiator circuit layout

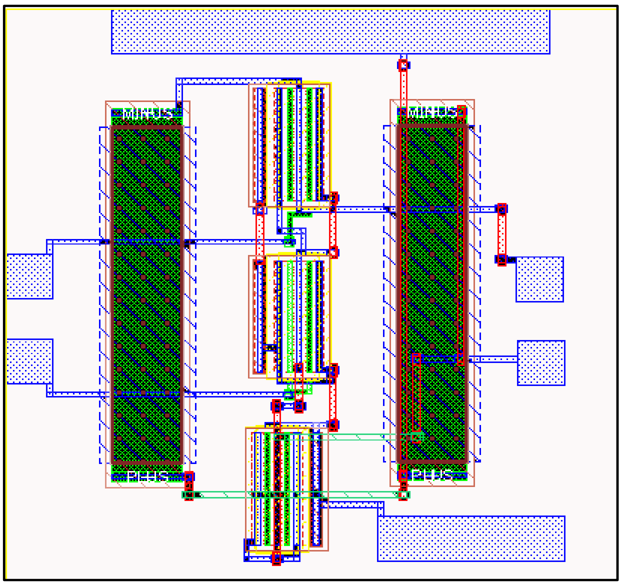

Figure 12: Differential circuit layout

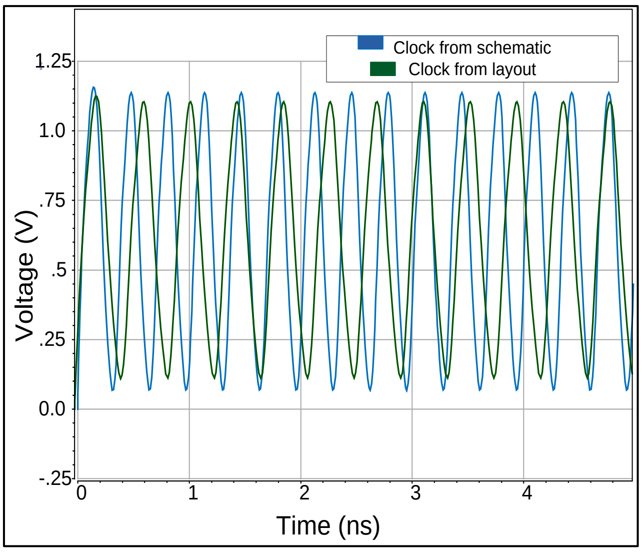

Figure 13: Layout and schematic output of CSVCO

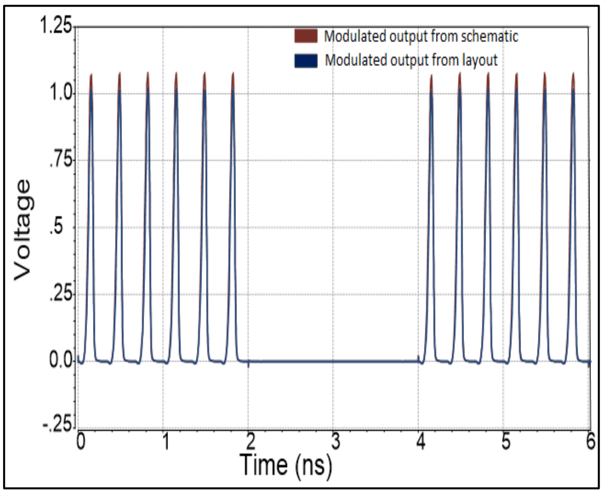

Figure 14: Layout and schematic output of OOK modulator

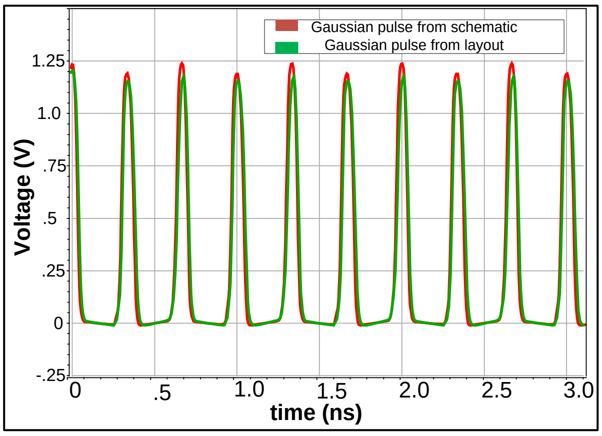

Figure 15: Layout and schematic output of GP generator

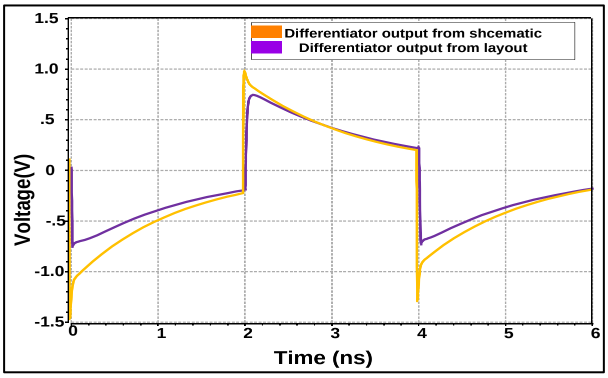

Figure 16: Layout and schematic output of differentiator

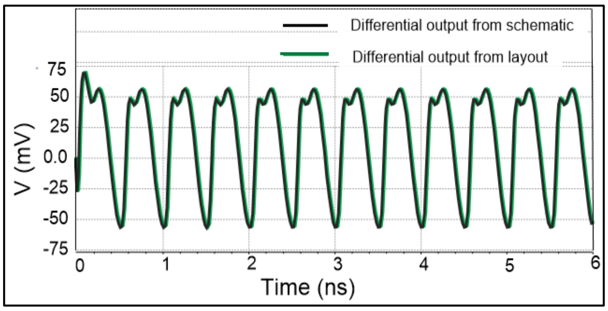

Figure 17: Layout and schematic output of Differential Amplifier

C. Process Corner Analysis of Designed Ultra-Wideband Transmitter

Any circuit based on devices generated at some of these process corners can function at high or low temperatures and voltages than needed, as well as slower or quicker than required (Osipov & Paul, 2017). As a result, an assessment of the suggested transmitter's process corners is also carried out to ensure that the designed transmitter functions properly at various process corners and temperatures.

The Simulated output for the NN, SS, SF, FS, and FF situations differs (Figure 16). Even, when the process or temperature change, the transmitter offers adequate pulse duration and bandwidth and pulse amplitude (Figure 19).

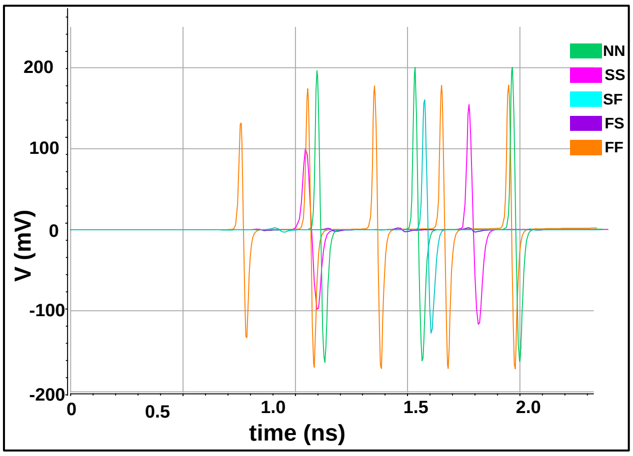

Figure 18: Output Gaussian pulse at (a) different process corner

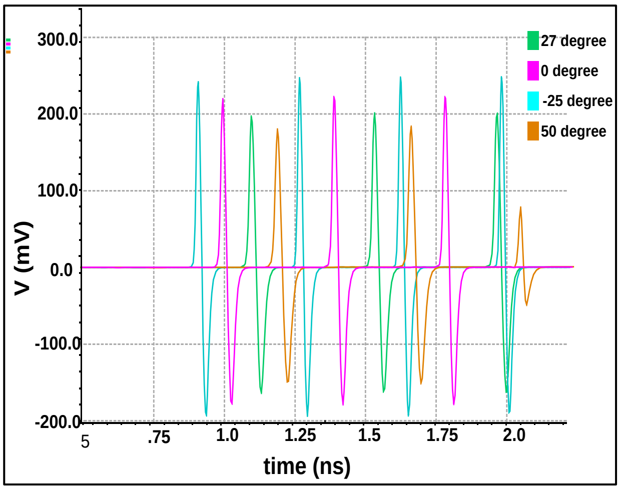

Figure 19: Output Gaussian pulse at different temperature

D. Simulated Outputs of transmitter and antenna using ADS software

Figure 20 illustrates the output GMP from proposed UWB transmitter simulated using ADS simulator which is same as the previously generated GMP from Cadence software. The return loss of the CPW fed UWB aperture antenna is shown in Figure 21. The suggested antenna fulfills the $-10\ dB$ return loss $(3.1 - 10.6)$ GHz.

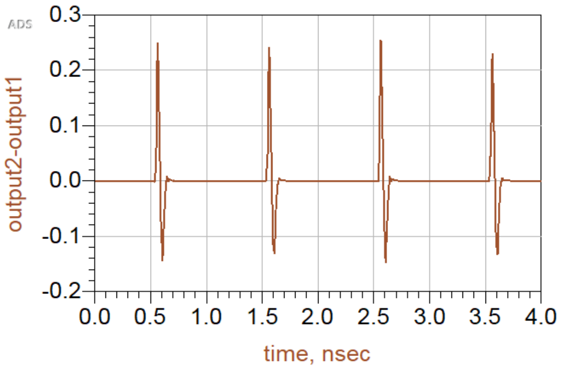

Figure 20: Output GMP from ADS simulator

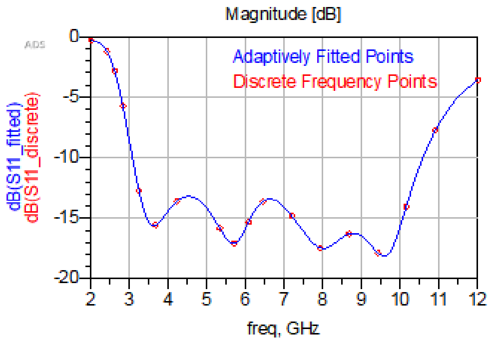

Figure 21: Return Loss of proposed UWB Antenna

The simulation of current distribution on the surface of proposed antenna at specified frequencies of 6 GHz and 10 GHz is shown in Figure 22 (Uwb & Itapu, n.d.). Figure 23 shows the s-parameter obtained from EM/circuit simulation of transmitter circuit and antenna (from circuit set-up of Figure 4).

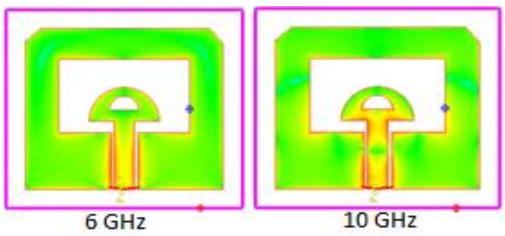

Figure 22: Simulated current distributions on the surface of the proposed antenna

Figure 23 depicts an ADS 3D representation of the proposed antenna's predicted radiation pattern at (6 GHz, 10 GHz). According to simulated result shown in Figure 23, the antenna has steady radiation patterns over the UWB, and the direction of greatest radiation is always around the z-axis (normal to the aperture plane). Figure 24 shows the antenna return loss after connecting the antenna with transmitter circuit which is obtained from EM/circuit co-simulation using ADS software. From this result it is seen that even after being connected with designed transmitter, the antenna fulfills the -10 dB return loss for ultra-wide bandwidth.

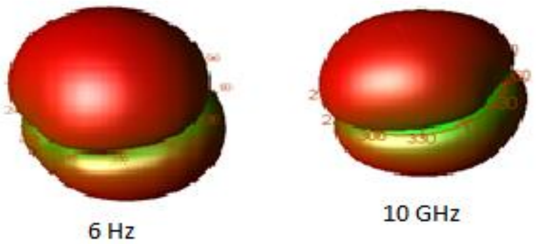

Figure 23: 3D plot of radiation pattern of proposed antenna

Figures 25 and 26 show the proposed antenna's gain, directivity, radiated power and absolute fields. Data was simulated at two different frequencies ($6\,GHz$ and $10\,GHz$). The information is displayed as 2-dimensional slices of a 3-dimensional radiation pattern.

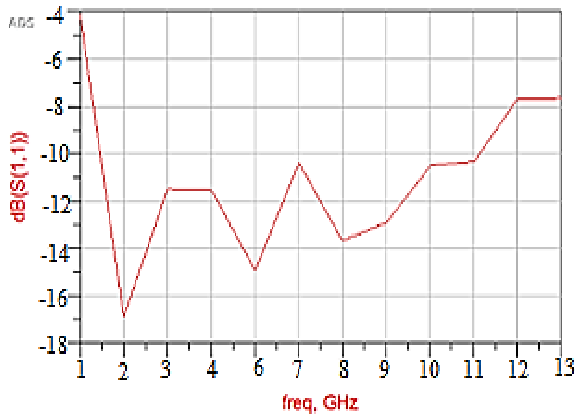

Figure 24: Antenna return loss from EM/circuit co-simulation

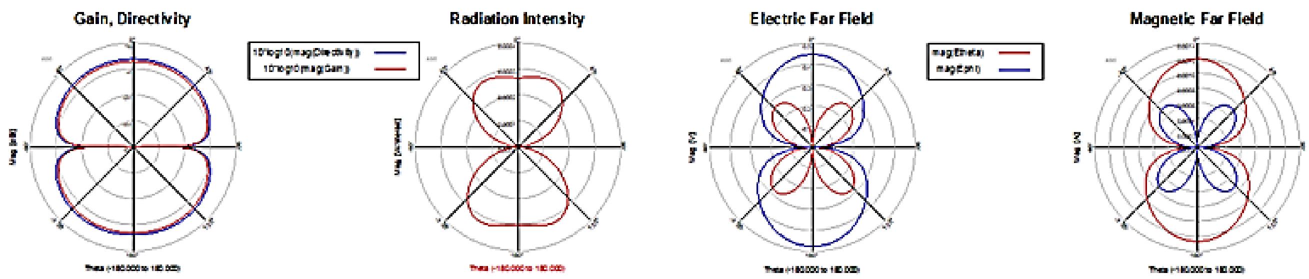

Figure 25: Gain, Directivity, Radiated power and Absolute Fields of the proposed antenna at 6 GHz.

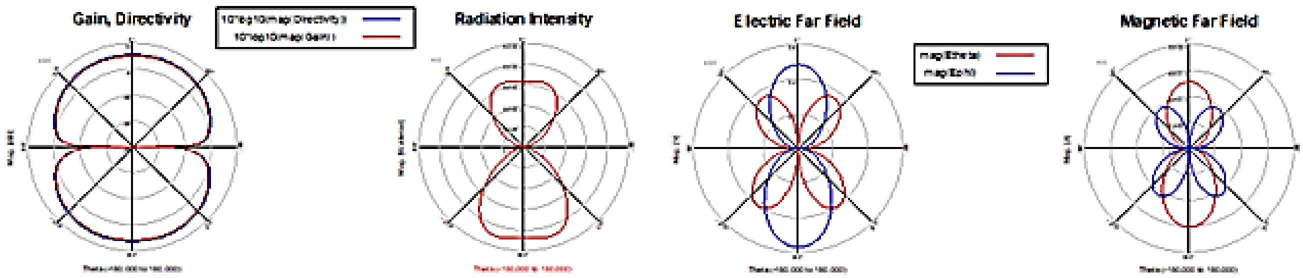

Figure 26: Gain, Directivity, Radiated power and Absolute Fields of the proposed antenna at $\mathbf{10}\ \boldsymbol{GHz}$

Table 2
Comparison of Presented Transmitter Parameters with Previous Works

Ref	Technology	Si Area (mm²)	Power Con. (mW)	Energy (pJ/b)	Output Pulse width (ps)	Modulation technique
(Lo *et al.*, 2013)	180nm CMOS	1.37 x 1.37	11.8	98.3	1000	OOK
(Radic *et al.*, 2020)	180nm CMOS	0.63 x 0.63	1	5	600	OOK
(Bahrami *et al.*, 2015)	180nm CMOS	0.10 x 0.10	5.4	10.8	800	OOK
(Notch *et al.*, 2013)	90nm CMOS	1.38 x1.38	26.4	65	2500	BPSK
This work	**90nm CMOS**	**0.065x0.073**	**0.831**	**3.324**	**100**	**OOK**

To illustrate the contribution of this research work in the field of UWB transmitter in medical applications, above table is presented which is showing in the comparison between the important output parameters of the presented transmitter with other reference papers which were followed during this work.

9. CONCLUSIONS

Because of its less complex circuitry and low consumption of power, a UWB transmitter is ideal for medical devices applications, remote patient monitoring wireless networking, intra chip communication and short distance local area networks. The presented structure consumes 0.831 mW power in total. This study proposes a complete impulse radio-based UWB transmitter on 90nm CMOS technology along with antenna. The simulated output waveforms obtained demonstrate the transmitter's capability. It is also possible to use a higher-order differentiator circuit. Other Gaussian pulse derivatives can also be constructed with intra chip silicon UWB antenna in the future.

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