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Frequency Notching Applicable to CMOS Implementation of WLAN Compatible IR-UWB Pulse Generators

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***Abstract*—Due to overlapping frequency bands, IEEE 802.11a WLAN and Ultra Wide-Band systems potentially suffer from mutual interference problems. This paper proposes a method for inserting frequency notches into the IR-UWB power spectrum to ensure compatibility with WLAN systems. In contrast to conventional approaches where complicated waveform equations are used, the proposed method uses a dual-pulse frequency notching approach to achieve frequency suppression in selected bands. The proposed method offers a solution that is generically applicable to UWB pulse generators using different pulse waveforms. In addition the method can be easily implemented. A prototype UWB pulse generator designed using the proposed method has been fabricated in a standard 0.18 μm CMOS process for verification, and satisfactory results are found.**

***Index Terms*—CMOS implementation, Frequency notching, IR-UWB, Pulse generator, WLAN compatibility.**

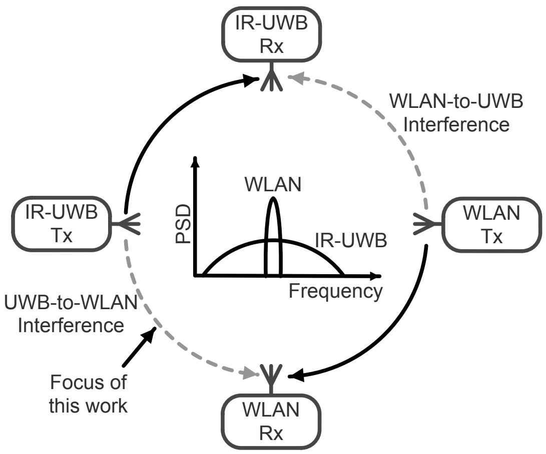


Fig. 1. The compatibility issue between UWB and WLAN systems.

I. Introduction

Owing to its attractive potential of low power implementation, multi-path robustness, localization etc., Impulse-Radio Ultra Wide-Band (IR-UWB) has been increasingly employed for short range applications, such as wireless sensor networks, biomedical applications and RFID [1], [2]. The deployment of IR-UWB wireless transceivers is for most of these applications usually in environments where other narrow band communication systems are present. Some of the narrow band systems, such as GSM, GPS and Bluetooth, operate in frequency bands that fall outside of the main UWB band (3.1-10.6 GHz) and therefore present no direct compatibility issues for their co-existence with the UWB system. IEEE 802.11a WLAN systems, however, operate in the 5.15-5.35 and 5.725-5.825 GHz frequency bands and may therefore give rise to significant mutual interferences [3]. As shown in Fig. 1 the problem can be WLAN-to-UWB interference or UWB-to-WLAN interference, where the victims are the UWB receiver and the WLAN receiver, respectively. The focus of this paper is on the mitigation of the UWB-to-WLAN interference.

Existing methods used to mitigate UWB-to-WLAN interference issues can be categorized into one of three groups: 1) Use only one of the sub UWB bands, e.g. 3-5 GHz or 6-10 GHz [4]; 2) Use antennas or filters with a frequency notch to suppress the UWB signal in the 5-6 GHz WLAN band [5], [6]; 3) Use special waveforms to realize a frequency notch at 5-6 GHz in the power spectral density (PSD) of the 3-10 GHz UWB pulse signal [7], [8]. Methods belonging to the first group are the simplest, but the frequency efficiency is low as the UWB frequency band is not fully utilized. This can reduce the achievable system communication range or data rate. The second group of methods is also reasonably straight forward to implement. The drawback here is that the methods increase circuit complexity and it is challenging to maintain good radiating/filtering performance (for example low insertion loss and return loss) while inserting a notch into the UWB band. Approaches belonging to the third group hold the potential to obtain high frequency efficiency as it uses both the lower and upper UWB bands. In addition, it also features high power efficiency since no generated in-band power is rejected or filtered out. Therefore increasing research effort has been put into this area [8], [9]. However, one drawback of these approaches is that the special waveform equations needed usually are based on infinite series or integral equations, such as the example below [7]

$$\lambda_k \psi_k(t) = \int_{-T_p/2}^{T_p/2} \psi_k(x) \frac{\sin W_k(t-x)}{t-x} dx, \qquad (1)$$

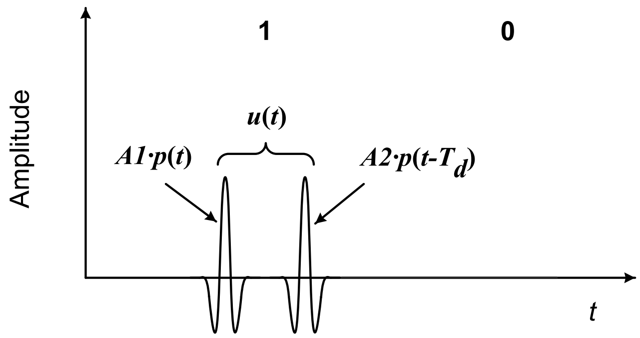


Fig. 2. The combination of two pulses with a relative time delay of T_d.

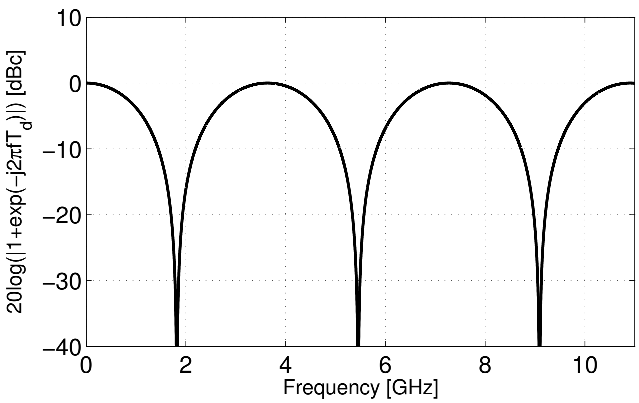


Fig. 3. The notched frequency bands introduced by the time delay between two identical pulse signals ($T_d = 275$ ps and the spectrum is normalized).

where $\psi_k(t)$ is the kth sub-band waveform, and the waveform with frequency notch is the sum of N sub-band waveforms

$$\psi_{mul}(t) = \sum_{k=1}^{N} \psi_k(t). \quad (2)$$

The implementation of such signals is complicated and therefore also very challenging.

This paper presents a simple method that makes it possible to insert frequency notches in the PSD of the UWB signal. This is accomplished using a dual-pulse frequency notching (DPFN) approach. The DPFN approach requires no special waveform equations and may thus be implemented using well known UWB waveforms.

II. The Dual-Pulse Frequency Notching Method

When looking to generate UWB pulse signals many different pulse waveforms may be used. Well known examples include the Gaussian pulse and its derivatives [10], [11], raised cosine pulses [8] etc. In this paper any one of these waveforms is generically represented by $p(t)$. As shown in Fig. 2, the proposed method uses two basic pulses to form a pulse signal $u(t)$. $A1$ and $A2$ are the amplitudes of the original pulse and the delayed pulse, respectively. In the ideal case the two pulses have identical shapes and amplitudes ($A1 = A2$). The only difference is a short relative time delay, T_d, between the two pulses. Based on this, $u(t)$ is expressed as

$$u(t) = A1{\cdot}p(t) + A2{\cdot}p(t - T_d). \quad (3)$$

For UWB systems using on and off keying (OOK), every combined waveform of $u(t)$ represents a bit "1".When $A1 = A2 = A$ the Fourier transform of $u(t)$ can be found as

$$U(f) = P(f)(1 + \exp(-j2\pi f T_d)), \quad (4)$$

where $U(f)$ and $P(f)$ are the Fourier transform of $u(t)$ and $A{\cdot}p(t)$, respectively. Assuming that the power spectral density of $A{\cdot}p(t)$ is $\Phi_p(f)$, the PSD of $u(t)$ can be found by

$$\Phi_u(f) = \Phi_p(f)|1 + \exp(-j2\pi f T_d)|^2. \quad (5)$$

It can be seen that $\Phi_u(f)$ is the product of an envelope term, $|1 + \exp(-j2\pi f T_d)|^2$, and the PSD of $A{\cdot}p(t)$. The envelope term is plotted in Fig. 3 for a T_d of 275 ps. Frequency notches are located at frequencies given by

$$f_k = \frac{1 + 2k}{2T_d},\ k = 0, 1, 2..., \quad (6)$$

where f_k is the central frequency of the kth notch. Thus by adjusting the time delay between two identical pulses frequency notches can be inserted at desired frequencies. When using $T_d = 275$ ps the second frequency notch is located at 5.5 GHz which improves compatibility with WLAN. In addition, the first notch is located at 1.82 GHz which improves compatibility with GPS and bluetooth systems.

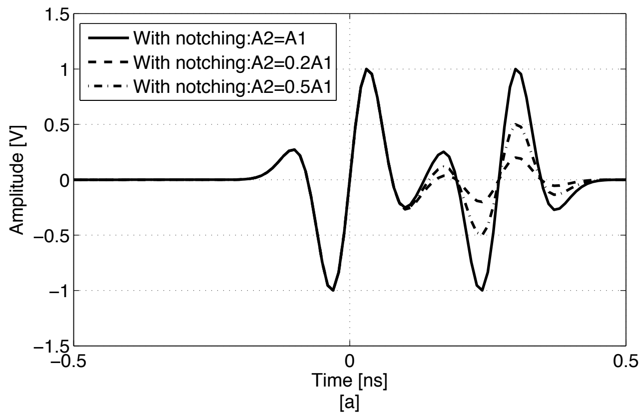
A. Application to the 3rd derivative of Gaussian pulse

As can be seen in (5) the frequency notching introduced by the envelope term, $|1 + \exp(-j2\pi f T_d)|^2$, is independent of the specific waveform used for the basic pulse $p(t)$. This means that the proposed method can be generically applied to different basic UWB waveforms.

The 3rd-order derivative of the Gaussian pulse is widely used in UWB pulse generators due to its easy circuit implementations and for that reason this pulse shape is used here as an example for the proof of the proposed concept. In this case, $A{\cdot}p(t)$ in (3) is

$$g^{(3)}(t) = A\left(\frac{3t}{\sqrt{2\pi}\sigma^5} - \frac{t^3}{\sqrt{2\pi}\sigma^7}\right)\exp\left(-\frac{t^2}{2\sigma^2}\right), \quad (7)$$

and for the case of $A = 1$, $\sigma = 43$ ps and $T_d = 275$ ps, the waveform of $u(t)$ in (3) is shown in Fig. 4(a), and its normalized PSD is shown in Fig. 4(b). As a reference, the normalized PSD of the third derivative of Gaussian pulse without notching (single pulse) is also shown in Fig. 4(b). By comparison it can be seen that the magnitude suppression achieved in the WLAN frequency bands is in excess of 10 dB. As an added benefit the first frequency notch provides the attenuation needed for the 3rd-order derivative of the Gaussian pulse to meet EIRP requirements. In any practical design, however, tolerances and mismatch issues always limit performance. For the proposed method such imperfections could easily result in an amplitude difference between the two



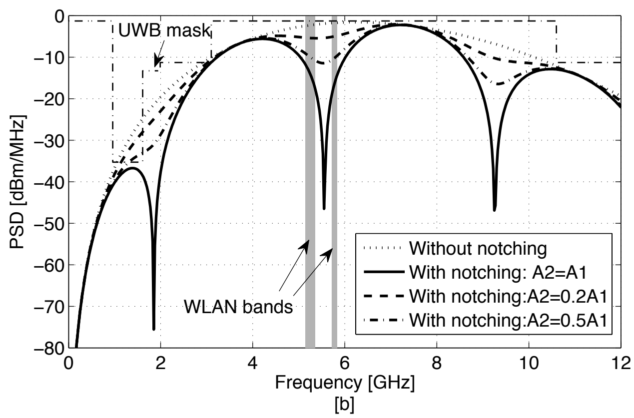


Fig. 4. The application of the proposed method on a UWB pulse signal using two 3rd order derivative Gaussian pulses. a) The pulse in time domain and b) its normalized power spectral density.

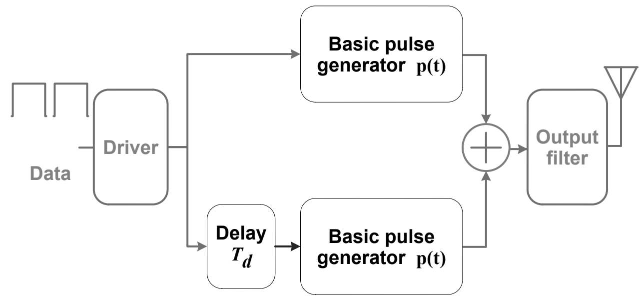


Fig. 5. The block diagram illustrating the implementation of the proposed frequency notching method using CMOS technologies.

pulses. Fig. 4 reveals the effect of different pulse amplitudes and it is clearly seen that the notching level is reduced in this case. However, despite a 1:2 relation between the pulse amplitudes the method still provides for > 8dB of suppression for both the WLAN bands. In addition it is seen that the locations of the notches are maintained.

III. CMOS Implementation and Experiment

A block diagram of the implementation of the proposed method is shown in Fig. 5. The highlighted basic pulse generator (BPG) and time delay block are for generating the basic pulse $p(t)$ and time delay T_d in (3), respectively. The time delay block can be realized by CMOS time delay cells, which can provide fine delay time in the order of hundreds of ps [12]. The BPG can be implemented using any CMOS-friendly UWB pulse generator, which can be easily found in publications. To achieve an optimal frequency notching level, the two basic pulse generators should be identical, and this can be ensured by using the same generator topology and identical layouts.

It should be noted that the total power efficiency of the two basic pulse generators is almost the same as that of a single pulse generator. This is because the output power is also doubled while the two basic pulse generators consumes doubled power. The delay block adds power consumption to the whole circuit. But this is insignificant compared to the power consumption of the BPGs as the delay block usually consists of only a few small-sized inverters.

A UWB pulse generator has been implemented using a standard 0.18 μm CMOS process to verify the proposed frequency notching method. The circuit schematic of the pulse generator is shown in Fig. 6. A widely used CMOS UWB pulse generator is employed in the design to show the generic application potential of the proposed method. The specific pulse generator implementation results in 1st-order derivative Gaussian pulses [13], [14]. The delay cell has two biasing voltages, which provide the possibility of adaptive tuning of the notched frequencies. The output filter is included to suppress the signal spectrum content in the 0-3 GHz band. Equivalently, the filter converts the low order derivative of Gaussian pulse to higher order derivative. SPICE simulations have been conducted to validate the implemented pulse generator in Fig. 6. Fig. 7 shows the simulated PSD of the generated UWB pulse signal using DPFN (two basic pulse generators). The PSD of the UWB pulse signal without DPFN (one basic pulse generator) is also shown in the figure. It can be seen that DPFN introduces frequency notches at desired frequencies. When $Vctr1$ and $Vctr2$ are 1.2 V and 0.72 V respectively, the frequency notches are located at 1.8 GHz, 5.45 GHz and 9.1 GHz, which are very close to those in Fig. 4.

The microphotograph of the fabricated test chip is shown in Fig. 8. The chip size is 0.7 mm by 0.7 mm including measurement pads. The layout of the two basic pulse generators is identical aiming for identical pulse waveforms and amplitudes. In the measurements a 125 MHz pulse generator PM 5785 from Philips™ was used as the data source and the PSD of the output signal was measured using a Rohde and Schwarz™ FSQ26 signal analyzer. The measured PSD of the UWB pulse signal is shown in Fig. 9. It can be clearly seen that three frequency notches are created at about 1.8 GHz, 5.4 GHz and 8.4 GHz, similar to the results in Fig. 4. The notch at 5.4 GHz results in an attenuation of about 4.5 dB, which is lower than the ideal case in Fig. 4 but still comparable to the suppression using frequency notched antennas (suppression $<$

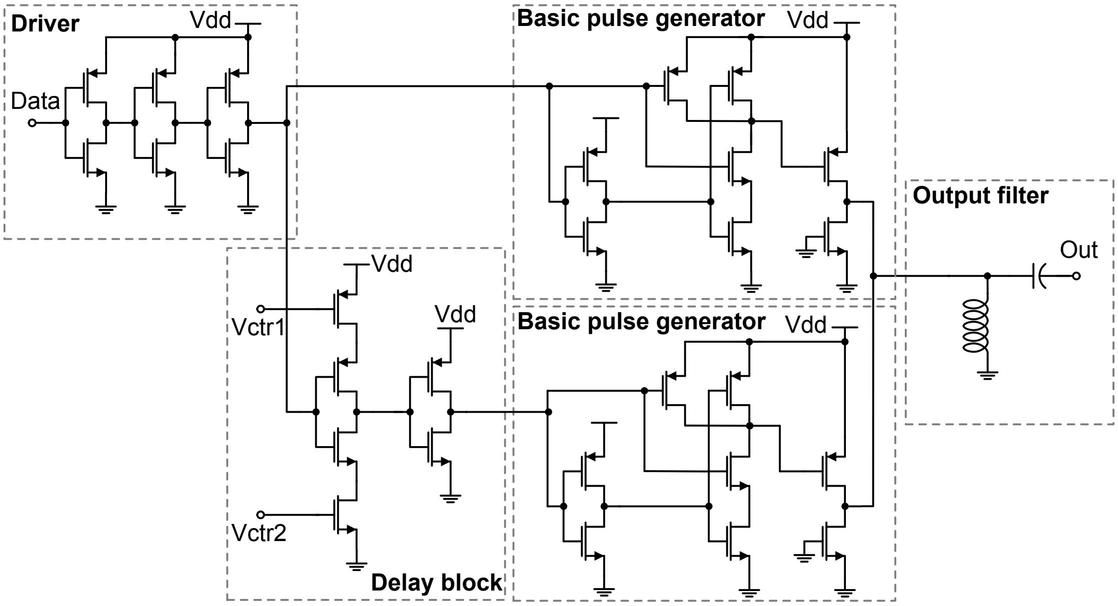


Fig. 6. Schematic of the circuit implementation of a UWB pulse generator using the proposed dual-pulse frequency notching approach.

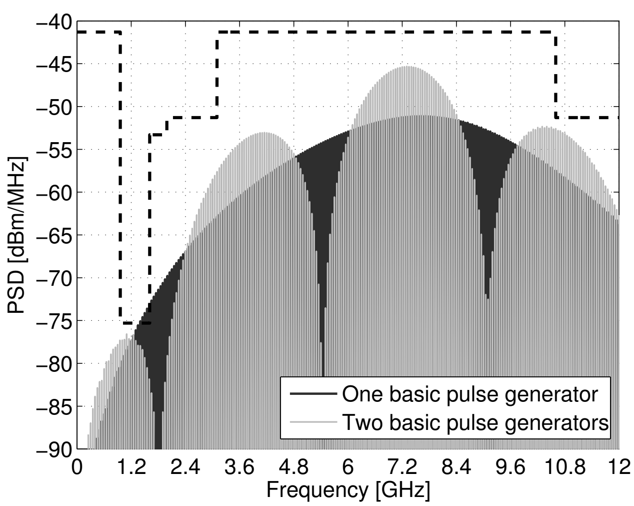


Fig. 7. Simulated PSD of the UWB pulse signal generated by the circuit shown in Fig. 6 (both BPGs), and the PSD using only the upper BPG (the lower one is disconnected). The pulse repetition frequency is 50 MHz.

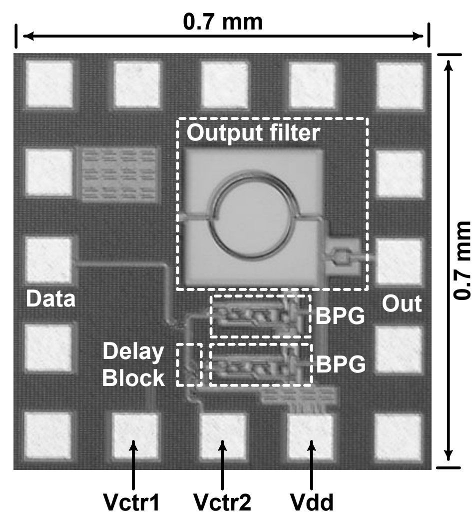


Fig. 8. The microphotograph of the test chip fabricated using a standard 0.18 μm CMOS process.

5 dB in [5]). This might be due to the asymmetrical layouts of the basic pulse generators, even though the generators have identical layouts. The asymmetrical layouts could lead to different rising/falling time of the input signal for the two pulse generators, and consequently introduce a waveform difference in the generated pulses.

In addition, violations of the UWB mask are observed at about 1.2 GHz and 3 GHz. This could be solved by the use of higher order derivative gaussian pulses that have lower spectrum content at low frequencies in comparison to lower order derivatives [13], [14]. Fig. 10 shows the SPICE simulated PSD of UWB pulse signals using the proposed DPFN method on basis of two 3rd, 4th and 5th order derivative Gaussian pulses. Compared to the PSD of 3rd order derivative Gaussian pulse, the frequency content of the case using 5th order derivative Gaussian pulse is significantly reduced by >20 dB and >10 dB at 1.2 GHz and 3 GHz, respectively. The whole PSD also fulfills the FCC's UWB mask.

IV. Conclusion

This paper presents a dual-pulse frequency notching approach that makes it possible to insert notched frequency bands in the PSD of IR-UWB pulses. This approach can be generically applied to widely used pulse waveforms as the notching is independent of the specific pulse waveforms. The proposed

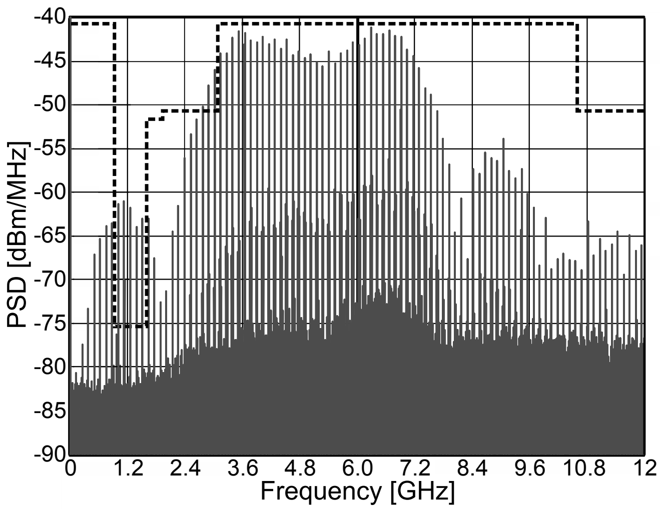


Fig. 9. Measured PSD of the UWB pulse signal with frequency notches. The pulse repetition frequency is 125 MHz.

method is simple and requires no complicated waveform functions, and therefore it can be easily implemented using CMOS technologies. A test chip fabricated using a standard 0.18 μm CMOS process has been used for experimental demonstration and a 4.5 dB magnitude suppression was measured in the WLAN band. It can be useful for mitigation of UWB-to-WLAN interference in the design of IR-UWB systems.

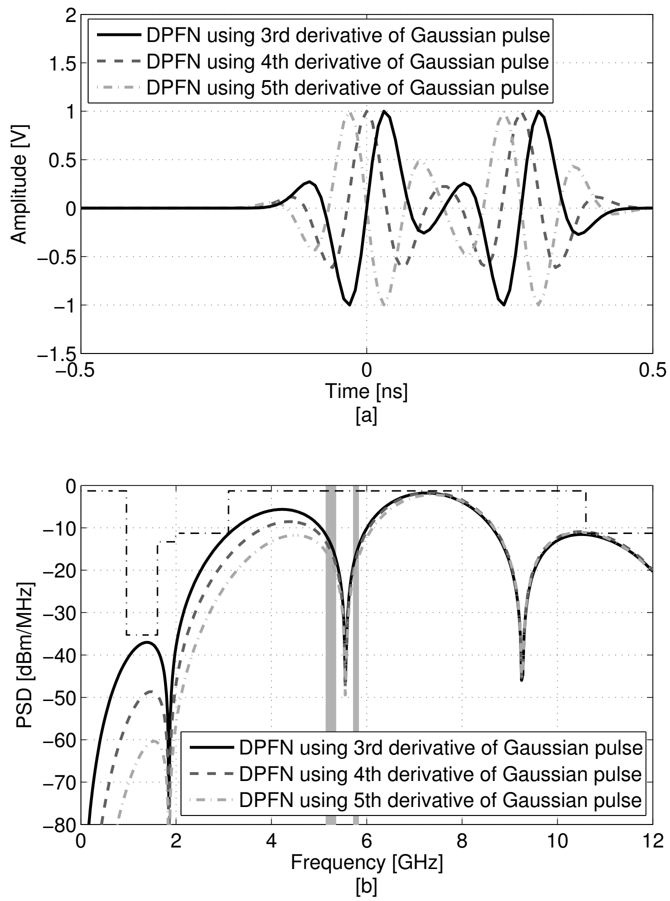


Fig. 10. Dual-pulse frequency notching using 3rd, 4th and 5th order derivatives of Gaussian pulse. a) in time domain and b) their power spectral densities.

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