UWB Pulse Generation in the 3.1-5.1GHz band

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***Abstract*— This paper introduces a new transmitter architecture including pulse generator and antenna dedicated to UWB radio communication in 3.1-5.1GHz band and targeting sensor and BAN applications. Firstly, pulse model parameters are specified through spectral and power analysis. Then, a pulse generator architecture is proposed followed by a study of radiated pulse through wideband and narrowband antennas for comparison.**

***Index Terms*— Ultra-Wideband (UWB), Impulse Radio (IR), Low Data Rate (LDR), Transmitter, Pulse Generator, Antenna.**

I. INTRODUCTION

While the deployment of UMTS starts, manufacturers are studying systems of 4th generation (4G) right now. This new generation puts forward convergence between wireless systems, including ultra wideband (UWB) high data rate up to 500Mbps. Next to these developments, UWB impulse radio is also a promising technology for low power consumption, low data rate communication up to 1Mbps – called UWB-LDR – and offers new capabilities with location and fine positioning in applications like sensor networks and body area networks (BAN).

II. WHAT IS ULTRA WIDEBAND IMPULSE RADIO ?

A. Principle of UWB Impulse Radio

Recently approved by the Federal Communications Commission (FCC), the UWB-IR (Impulse Radio) technology uses an ultra wide frequency band in order to transmit information under existing systems noise level. UWB signals are usually defined as signals having an instantaneous 10dB bandwidth of at least 20% of the center frequency or at least 500MHz [1]. Modulated in position (PPM), in polarity (BPSK) or in amplitude (OOK), generated pulses with short duration (typically 2ns) are used to spread information over the whole allowed band.

B. Normalization

In reference to FCC, an UWB system is allowed to transmit information in the 3.1-10.6GHz band for all types of communication systems. In this band, FCC allows a maximum average power level of -41.3dBm/MHz and a maximum peak power level of 0dBm/50MHz [2]. Currently in Europe, no emission mask is standardized but some suggestions have been published by ETSI.

C. Restriction to the 3.1-5.1GHz sub-band

Because of high interference by WLAN in the 5-6GHz band, we decided to use only the lower part of the upper band: the 3.1-5.1GHz band. Moreover, this choice involves some advantages in term of system complexity and performance: by using a band below 5GHz, circuit consumption is reduced due to the technology employed and antenna complexity is also scaled-down to a 50% relative bandwidth or less.

III. SPECTRAL AND POWER ANALYSIS

An UWB radio communication system uses pulses as an information support. In the case of simple modulation like OOK associated with asynchronous receiver, the main function of pulses is to carry energy; thus temporal shape is not predominant. Considering this, the main characteristic of a pulse is to have a power spectral density (PSD) included in the 3.1-5.1GHz band with a maximized energy.

A. Windowed cosine pulse model

The idea of using a windowed cosine pulse model comes from the possibility of controlling oscillations and envelop separately. Temporal expression of this pulse model is:

$$p(t) = A \exp\left(-\frac{t^2}{2\sigma^2}\right)\cos(2\pi f_0 t) \tag{1}$$

where A is the maximum amplitude of pulse, σ the standard deviation of the zero-order Gaussian envelop and f_0 the frequency of the sinusoidal function. Single side-band (SSB) Fourier transform of (1) gives us:

$$P^+(f) = A\sqrt{\pi}\sigma \exp\left(-\frac{(2\pi\sigma(f-f_0))^2}{2}\right) \tag{2}$$

According to normalization, we have to find the optimal values for A, σ and f_0 in order to transmit the maximum energy per pulse. Let us note that the amplitude A is rather correlated with average and peak power limitations whereas σ and f_0 are correlated with emission mask.

B. Standard deviation and sinusoid frequency specifications

In order to maximize in-band spectral occupation, pulses must be as wide as possible in the 3.1-5.1GHz band. Because the pulse PSD is symmetrical around f_0, we choose $f_0 = 4.1$GHz, the in-band center frequency.

Then, in case of FCC outdoor power limitation mask which is the most constraining, pulse PSD must be 20dB lower than the maximum, $|P^{+}(f_0)|^2$, at in-band limits which are 3.1GHz and 5.1GHz. Then, σ is given by solving:

$$10\log_{10}\left(\frac{|P^{+}(f)|^2}{|P^{+}(f_0)|^2}\right)\Bigg|_{f=3.1\text{GHz}/5.1\text{GHz}} = -20\text{dB} \tag{3}$$

We obtain $\sigma = 341\text{ps}$ which corresponds roughly with a 2ns time-domain pulse width.

C. Pulse amplitude specification

To specify a maximum for pulse amplitude, we estimate the pulses train average and peak powers. We suppose that measurements are done through a spectrum analyzer with a resolution filter bandwidth (RBW) of 1MHz for average and 3MHz for peak power measurements.

We conclude that peak power limitation is more restrictive when we compare average and peak power estimations. We obtain a maximum of $A = 0.471\text{V}$ for pulses amplitude which corresponds to a 20.45dBm peak power for generated pulses. Details of this analysis are presented in [3]

D. Pulse model parameters results

In order to reach normalization in terms of power limitation and spectral occupation while energy per pulse is maximized, we must choose the following values for the windowed cosine pulse model: $A = 0.471\text{V}$, $f_0 = 4.1\text{GHz}$ and $\sigma = 341\text{ps}$. Pulse time and frequency domain representations with theses parameters values are shown in Fig. 1.

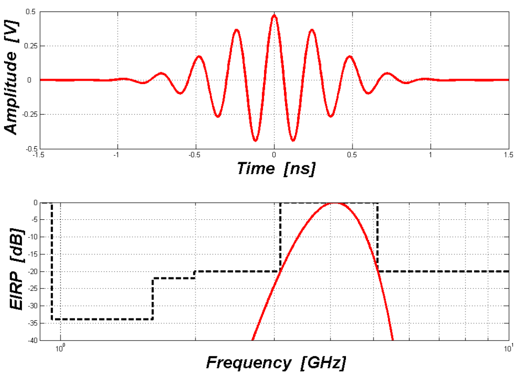

Fig. 1. Optimal pulse for the 3.1-5.1GHz band

IV. Pulse Generator Architecture

To the contrary of super-heterodyne architectures, an UWB transmitter architecture could be reduced to a digital part connected directly to an antenna. For a sub-band operation under 5GHz, a mixed analog-digital architecture seems to be a better choice in terms of low consumption capabilities.

A generic UWB transmitter architecture is done with a pulse generator followed by a modulator, all driven by a digital baseband system. Moreover, we use an amplifier to achieve required power, a filter to reduce spurious emission and a wideband antenna to radiate information.

A. Proposed architecture

Several pulse generators have already been developed, using solutions from analog to all digital. Meanwhile, most of them generate pulses with a shape close to the first-order derivative of a Gaussian which is not adjusted to the 3.1-5.1GHz band. Then, we developed the pulse generator architecture presented on Fig. 2 and based on the product of a sinusoidal signal with an envelop close to a zero-order Gaussian shape.

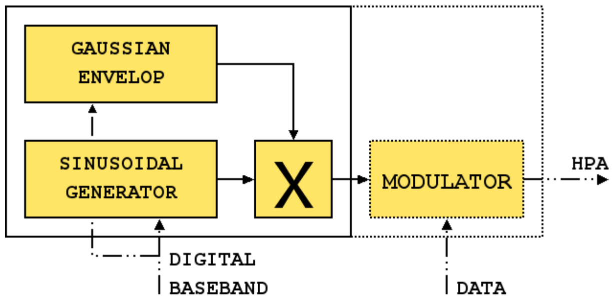

Fig. 2. Pulse generator architecture

In terms of design, sinusoidal signal is generated with a mostly digital periodic source. The latter is followed by a differential pair with a modulated current source to create a mixer function. Gaussian envelop is obtained by using a digital square signal filtered by a transistor input capacitor. Moreover, let us note that this architecture offers possibilities to integrate the modulator directly in the pulse generator.

B. Design specifications

Due to process variations and design considerations, elements of the generator cannot be perfect and main imperfections must be evaluated before design. In a first step, the main feature of a mixer for the proposed generator is the isolation between the output and the oscillator input; and about the oscillator, we have to take into account phase noise.

1) Mixer isolation: To evaluate required mixer isolation, we consider that oscillator is in "on state" during a time τ around the pulse. In this case, there is a spurious signal through the mixer which is modeled by an in-phase sinusoidal signal added to the mixer output. By defining mixer isolation I_m as the ratio of maximum to spurious amplitude, we evaluate again the pulse maximum amplitude, according to the peak power limitation.

Take an example with a 20dB mixer isolation and a τ of 5ns which correspond to targeted specifications, pulse maximum amplitude must be reduced to 0.317V in order to satisfy power restrictions.

2) Oscillator phase noise: Due to large bandwidth of generated signals, phase noise floor is predominant like phase noise due to period jitter which creates a noise floor around the carrier.

Through a time-domain approach, we use a model of a carrier with a period jitter. The noise floor created with that period jitter can be high enough to reach -75.3dBm/MHz (-34dB under PSD maximum) which correspond to FCC power limitation in 0.96-1.61GHz band (GPS band). By system simulation, we have established that period jitter of the oscillator must not be greater than 4.9×10^{-7}rad in order not to exceed this limit. This correspond to a -120.2dBc/Hz SSB noise floor level.

3) Real pulse generated: Fig. 3 shows an example of real pulse generated at generator output in case of I_m = 20dB, τ = 5ns and a SSB phase noise of -120.2dBc/Hz. All of these results concerning pulse

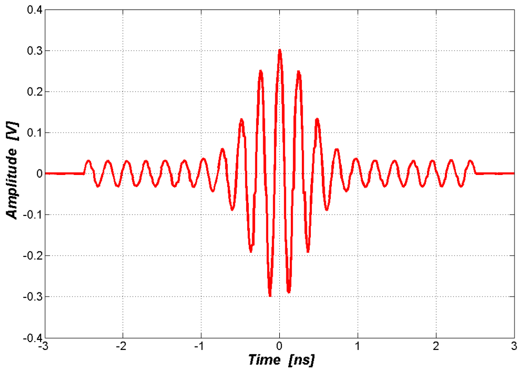

Fig. 3. Generator output pulse shape in case of $I_m = 20$dB, $\tau = 5$ns and a SSB phase noise of -120.2dBc/Hz

generator dimensioning are presented more in details through a theoretical approach in [3].

V. Antenna/Impulse co-design

Many articles present ultra wideband antenna design targeting impulse radio applications in the 3.1-10.6GHz band. In order to keep impulse integrity, an ultra wideband antenna requires mainly wideband matching and low distortion due to a constant phase center. For impulse radio applications in the 3.1-5.1GHz band, antenna constraints are not similar to a wider bandwidth and the use of a narrowband antenna could be suitable in restricted band for UWB applications.

In order to demonstrate that idea, we chose two antennas for comparison : a narrow band antenna – a $\lambda/2$ dipole – and a wideband antenna – a diamond dipole[5] –. Following simulations were done with CST-Microwave Studio[4] which is a time-domain electromagnetic simulator software.

A. Dipole antenna

A $\lambda/2$ dipole is a classical and well-known narrowband antenna. Length of dipole arms is set to have a resonant frequency at 4.1GHz. In our case, we have a length of 14.7mm for each copper arm and a spacing of 2mm between each arm. Wire diameter is 0.59mm. This antenna, for which design is shown on Fig. 4, presents a maximum gain of 2.17dBi.

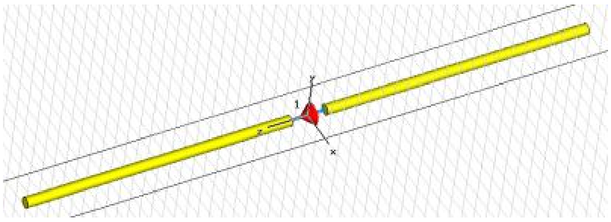

Fig. 4. Dipole antenna structure

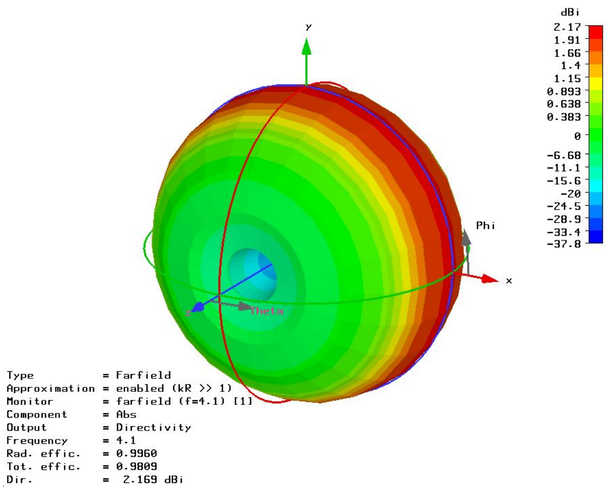

Fig. 5. 3D-directivity of dipole antenna

B. Diamond antenna

A diamond antenna is similar to a thick dipole which is composed with two isosceles triangles that are fed in differential through our base. Triangle height is equal to base width. We chose the triangle height such that the antenna frequency response is centered in 4.1GHz as in case of dipole antenna. Theses two triangles are supported mecanically with a 2.2 relative permittivity substrate and this antenna presents a 2.78dBi maximum gain. Its structure is shown Fig. 6.

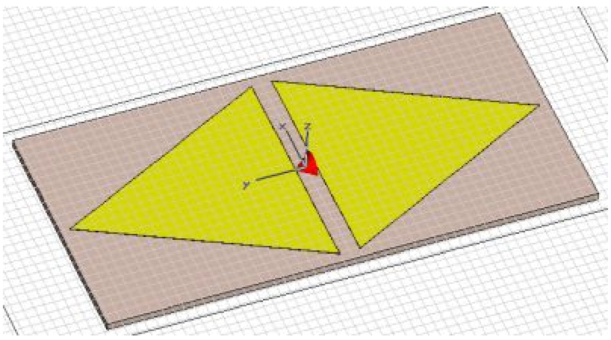

Fig. 6. Diamond antenna structure

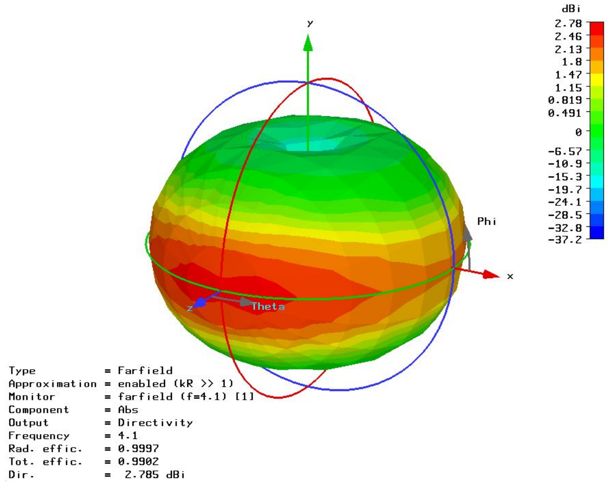

Fig. 7. 3D-directivity of diamond antenna

C. Comparison between antennas

Let us compare fequency- and time-domaine responses of theses two antennas through Voltage Standing Wave ratio (VSWR) and impulse response.

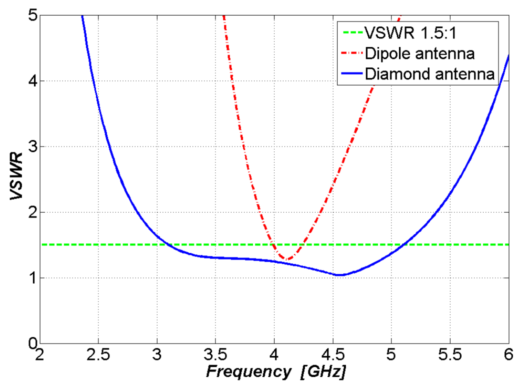

Fig. 8. VSWR of the two antennas with a 50Ω matching

Concerning VSWR shown in Fig. 8, the dipole antenna has a bandwidth of 250MHz with a VSWR of 1.5:1 which illustrates the narrowband antenna behavior. In case of diamond antenna, we have a bandwidth of 2GHz centered in 4.1GHz with a VSWR below 1.5:1 which is more or less constant.

Frequency-domain response can be correlated with time-domain response: the wider the antenna bandwidth is, the shorter the impulse time-domain response of the antenna is as shown in Fig. 9. This specification can be evaluated through simulation by observing the duration of antenna time-domain response. We observe that dipole antenna response presents more ringing than diamond antenna one.

It is clear that a dipole antenna cannot be used in 3.1-10.6GHz ultra wideband applications that use pulses similar to a Gaussian derivative due to high time-domain dispersion of the antenna (which is correlated to the narrow bandwidth).

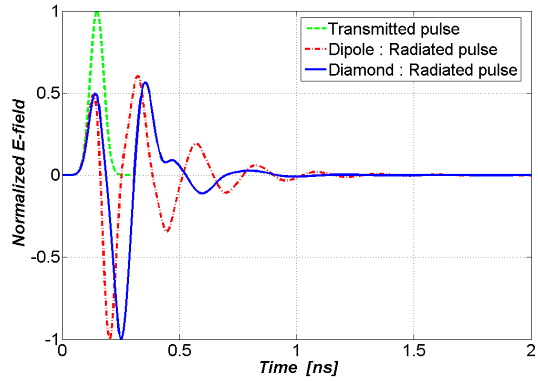

Fig. 9. Impulse response of the two antennas

D. Antenna response to a real generated pulse

Let us now consider a non-perfect pulse genenated with our generator. In this study, we chose the pulse presented before in this paper. Fig. 10, Fig. 11 and Fig. 12 presents time- and frequency-domain responses of antennas to a real pulse.

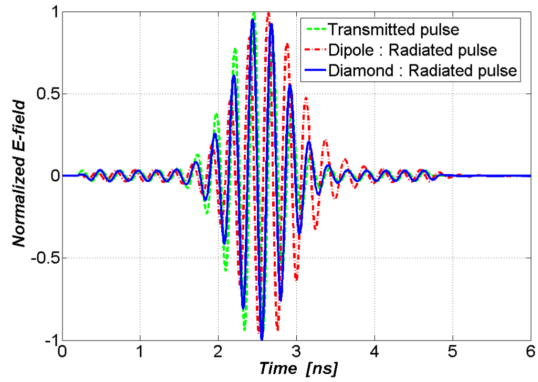

Fig. 10. Radiated E-field in the maximum of directivity

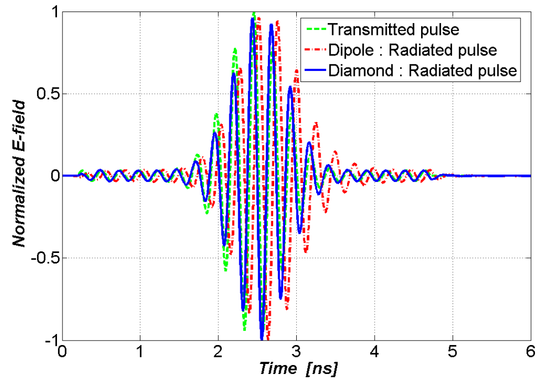

Fig. 11. Radiated E-field in the direction $\theta = 45/\phi = 45$

In time-domain, we observe a good correlation between transmitted and radiated pulses in both cases – in direction of maximum directivity and $\theta = 45/\phi = 45$ – and this for both antennas. Note that diamond antenna response is closer to reference due to its wider bandwidth. In case of dipole antenna, we observe an envelop rise and fall time more important than in case of diamond antenna.

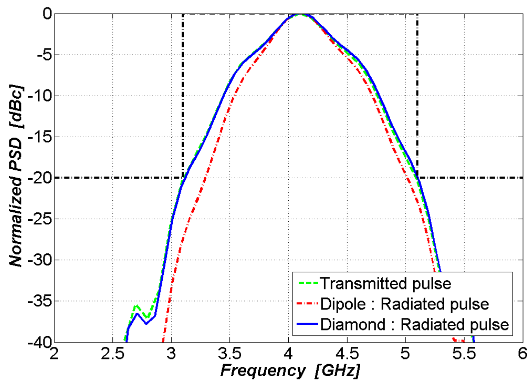

Fig. 12. FFT of radiated E-field in the maximum of directivity

In frequency-domain, we observe a very good correlation between transmitted pulse and diamond antenna radiated pulse as shown in Fig. 12. The dipole antenna presents a narrower frequency response than the diamond antenna due to its narrower bandwidth.

E. Why such dipole antenna radiates "good" pulses?

Observations presented below are very interesting for UWB Low Data Rate applications. The question is why a dipole presents this behavior ? In our case, we must think generated pulse as a modulated carrier and not as a impulse signal. An impulse signal excites antenna over the whole band in the same time while our generated pulse excites "only" the carrier frequency which is modulated in amplitude. Envelop variation or modulated signal around carrier frequency is slow enough so that the dipole antenna is able to follow its variations without spreading pulse in time-domain.

In this case, dipole antenna behavior is then closer to a narrowband excitation process than a wideband excitation process.

VI. CONCLUSION

Based on a windowed cosine pulse model, a new UWB pulse generator in the 3.1-5.1GHz band is presented in this paper, targeting LDR applications like sensors and BANs. We highlighted some design specifications concerning mixer and oscillator and put forward a new approach to antenna excitation process. Both dipole and diamond antennas are suitable for UWB-LDR applications. Then, antenna choice will be driven by the application which can require a planar antenna or a thin wire for example.

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