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Evaluation of the Brillouin precursor performance for ultra wide band intra-body technologies

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In this letter, we describe the formation and the evolution of Brillouin precursor fields through human tissues by using a frequency-domain analysis technique and a multi-pole Cole–Cole model to characterize the dielectric properties of the human body tissues, in a frequency band designated by the FCC for ultra wide band medical applications, which extends from 0.5 to 20 GHz. A 3D representation of the human body model has been implemented by employing a discretized mesh of cuboids with a resolution of 8 mm^3 in which the frequency dispersive material parameters for different tissues have been considered. The dispersive propagation is analyzed for the purposes of radar imaging and intra-body communications. The performance of a classical rectangular pulse, a Brillouin pulse and a medium-matched waveform is described. The results show the potential application of this type of communication scheme in order to improve the achievable measurement range and provide better signal to noise ratios.

Keywords: Brillouin precursor; frequency dispersion; power extinction; ultra wide-band

1. Introduction

The frequency dependence of the dielectric properties of human body tissues can severely affect the performance of both radar imaging and intra-body communications. [1,2] It has been theoretically demonstrated [3,4] that an electromagnetic field named precursor or forerunner emerges superimposed on the original signal transmitted after travelling through any dispersive media, such as water, soil, vegetation and human tissues. Theoretically, it is shown that the formation of these fields guarantees the transmitted signal to reach a deeper propagation distance inside a medium. This fact is due to the algebraic peak amplitude decay trend of the travelling signal once the precursor arises, instead of a classical exponential decay trend related to the carrier component.

However, despite the evident advantage provided by the presence of a Brillouin or Sommerfield precursor component, the dispersive propagation has never been considered as a positive contribution. This is partially due to the fact that precursor field formation is influenced by a set of configuration parameters, specific for a dispersive medium and a transmitted signal, which can determine the optimal or inexistent

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formation of the precursor field.[4–7] A well-known impairment related to the dispersive propagation and the precursor field appearance is the larger time width duration shown by the received signal which corresponds, in the frequency domain, to a downshift of the carrier frequency. These issues have impelled the consideration of forerunners as a phenomenon which requires in-depth study.

Nevertheless, dispersive propagation affects many usual and emerging systems and applications, being of particular importance in the case of human tissues. High-resolution systems as employed in medical imaging require the use of ultra wide band waveforms and for such pulses the medium is inherently dispersive.[8] This will unavoidably lead the Brillouin or Sommerfield precursors to emerge even if they are not explicitly visible.[4] The ability to use precursor waveforms would greatly enhance the image quality at much larger penetration distances within a given medium. Hence, medical imaging applications could improve the signal-to-noise (SNR) ratio after increasing the amplitude of the received signal level.

For intra-body communications, the form and shape of the information-bearing transmitted signal is also an important factor to consider.[7,9,10] Since the transmitted signal influences the formation and performance of the resulting precursor, we can conclude that a medium-matched signal can lead to optimal performance by combining the benefits of the precursor formation (larger amplitude) with minor impairments (lesser time duration broadening).

In this letter, we analyze the evolution of the Brillouin precursor field as a tool to improve the electromagnetic propagation through dispersive human tissues. In Section 2, we introduce the formulation developed to analyze the dynamical evolution of a signal travelling through a dispersive medium.

Additionally, in Section 2, we describe the 3D human model developed to obtain a realistic interaction of precursors. We also present the selection of the parameters for a rectangular pulse, for a Brillouin pulse and for a medium-mismatched waveform in order to achieve optimum performance in the dispersive media considered. In Section 3, we present some simulation results: dynamical evolution and field intensity. Finally, conclusions are given in Section 4.

2. Formulation of dispersive propagation

Different approaches can be used to model the dispersive propagation, such as the uniform asymptotic method proposed by Oughstun et al. [3], an FDTD solution or an FFT-based analysis.[4,6,11]

Since the medium can be seen as a frequency-selective transfer function (i.e. as a filter) which affects in a different way the amplitude and phase level of each frequency component of any signal travelling through it, the evolution of any input signal $x(t, z=0)$ through the dispersive medium for any propagation depth z can be solved in the frequency domain and then an inverse fast fourier transform (IFFT) can be applied to observe the output signal $y(t,z)$ in the time domain, as indicated in (1):[4]

$$y(t,z) = \mathrm{IFFT}\{X(f,z=0)\cdot H_m(f,z)\} \quad (1)$$

where $H_m(f,z)$ is the frequency transfer function of the medium that can be approximated by the transmission coefficient of a plane wave through a dielectric slab [4] with a propagation constant $\gamma_m(f)$ (1/m). If a Fresnel transmission coefficient is assumed, the material frequency transfer function is given as in (2):

$$H_m(f,z) = e^{-j\gamma_m(f)z} \tag{2}$$

Generally speaking, for a realistic estimation, the transfer function of the dispersive medium would also take into account the boundary conditions due to the different media interfaces that interact with the signal along the propagation path. This requires the consideration of the transmission and reflection coefficients if the signal travels through layers of different media in order to take into account both impedance mismatch and internal propagation mechanism.[12,13]

2.1. Dielectric model

The model representing the complex dielectric properties of the underlying dispersive media is of vital importance since it is used to estimate the propagation constant $\gamma_m(f)$ in (2). The dielectric properties will fingerprint indeed the resulting Brillouin precursor.

The complex dielectric permittivity $\varepsilon_r(f)$ for a given material could determine the range of frequencies that are likely suitable to produce the precursor. The accuracy of the permittivity model is, therefore, relevant to predict the accurate dynamical evolution of the propagated signal.

In this letter, the multi-pole Cole–Cole dielectric model described in [14] has been considered to be suitable to characterize most of the human tissues, as given in (3):

$$\varepsilon_r(\omega) = \varepsilon_\infty + \sum_{j=1}^{3} \frac{a_j}{(1 - i\omega\tau_j)\cdot(1 - i\omega\tau_{fj})} + i\cdot\frac{\sigma_0/\varepsilon_0}{\omega} \tag{3}$$

where ε_∞ is the real part of the complex relative permittivity at DC and high frequency; τ_j is the rotational relaxation times; ω is the angular frequency in rad/s and σ_s/ε_0 is the DC electrical conductivity. The different parameters for each type of tissue are summarized in [14].

The Cole–Cole model is considered to be more accurate to represent human tissues at low frequencies under 200 MHz. However, it implies more computational complexity to input a Cole–Cole dispersion model into FDTD. Recently Debye models have been applied, which carry less computational overhead and the same accuracy level than the Cole–Cole model.[15] However, this complexity does not concern the frequency-based analysis previously discussed.

In order to realistically analyze the interaction of precursor waveforms, a 3D human body model of 1.80 m height has been implemented for this work following a simplified human body model described in [16] and depicted in Figure 1. This 3D human body representation results are extraordinarily worthy to analyze the evolution of precursor waveforms with plausible application in radar imaging and intra-body communications.

The human body model is parameterized in order to consider different heights and postures. In this particular case, the human body model has been divided in 8 mm·8 mm·8 mm cuboids leading to over 1500 horizontal planes and over 9000 transversal planes. The material parameters have been computed from 3 to 10 GHz, considering the frequency-dependent complex relative dielectric permittivity and conductivity for each organ within the respective cut planes.

For the purposes of this research work, we have considered the two horizontal cut planes shown in Figure 1, for a height of 1.20 and 1.35 m, in which several organs such as the stomach, pancreas zone and heart are visible.

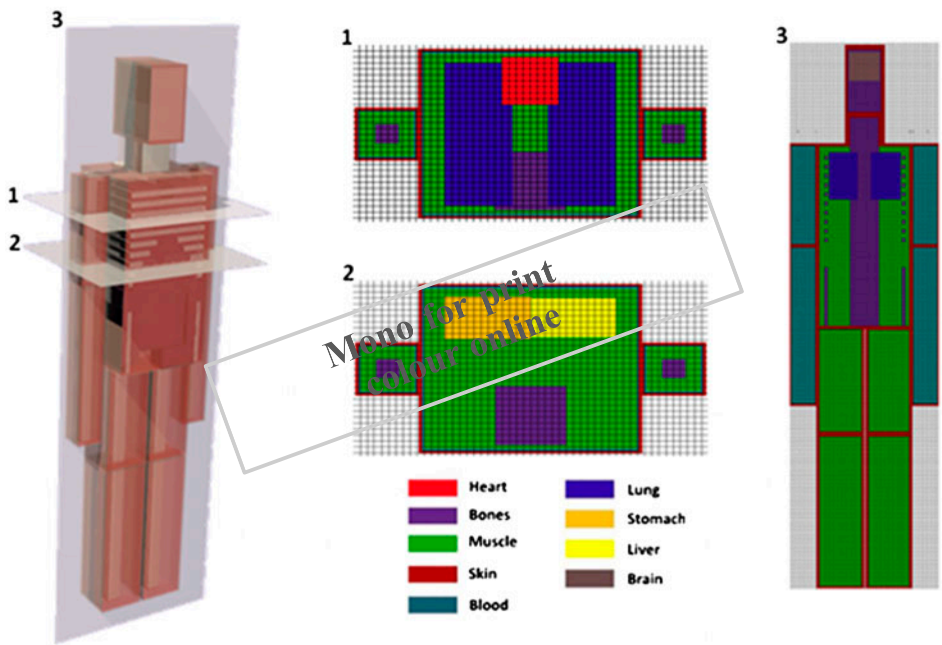

Figure 1. Schematic representation of the implemented human body model, with longitudinal (1,2) and transverse (3) planes dotted of colour grading for the material properties considered for each one of them.

2.2. *Transmission pulses*

For the purposes of this letter, the transmitted signal $x(t)$ consists of a pulse $p(t)$ modulating a sine carrier f_0. The rectangular pulse just involves one parameter, the pulse width or period, T_b: $p(t)=\prod(t/T_b)$, $0\leqslant t\leqslant T_b$. We have selected a multi-cycle setting with $T_b=10/f_0$.

For the Brillouin pulse we have considered the formulation described in [7]. This near-optimum waveform aims to achieve the maximum penetration depth into a dispersive medium. It is composed of two Brillouin signals, the second one shifted π radians and delayed by ΔT, so that the broadening produced due to the Brillouin precursor formation does not lead to overlapping of both cycles.

For the mismatched pulse, it is necessary to apply a medium-mismatched signal to the transmitted pulse, given by $X(f,z=0)\cdot H_m(f,z)$. Once propagated to a distance z through the dispersive channel, the input pulse does not undergo any time width broadening or shape distortion due to cycle overlapping.

3. Simulation results

In Figure 2, we show the input waveforms considered in this letter. In Figure 3 the dynamical evolution of a rectangular pulse for different propagation depths expressed in its relative form z/z_d, with $z_d=1/\alpha(f=f_0)$ meters is depicted. It can be seen that at distances $z=5\cdot z_d$ or greater, only the precursor component retains energy, whilst the intermediate cycles corresponding to the carrier term fully extinguish.

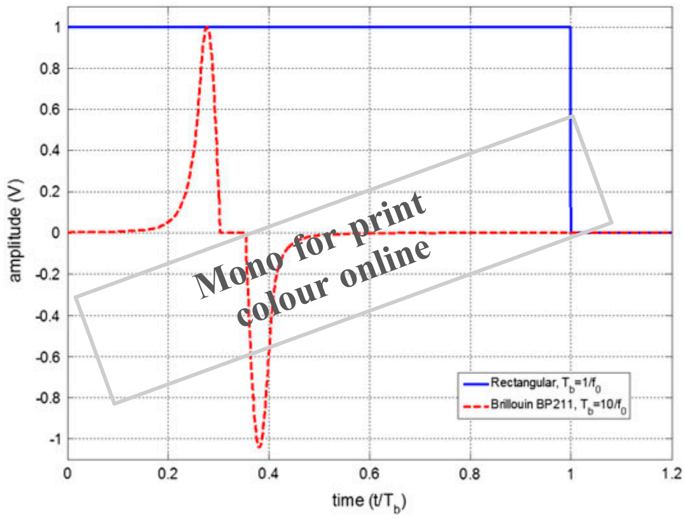

Figure 2. Input waveforms: baseband rectangular and Brillouin pulses.

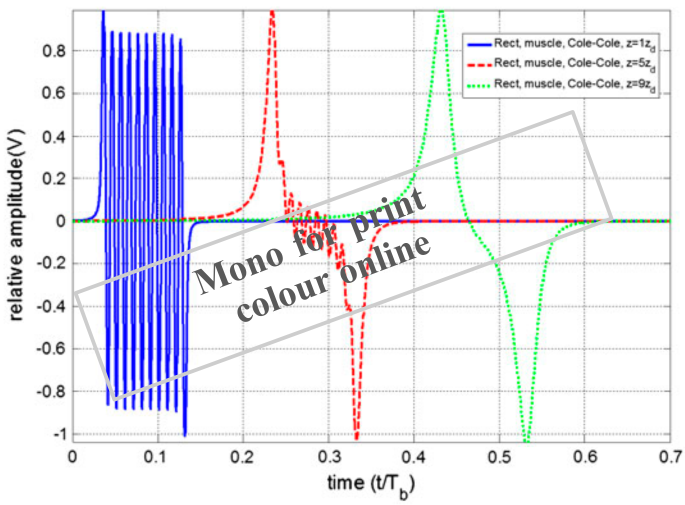

Figure 3. Dynamical evolution of normalized field through different propagation distances within a single layer of muscle (Cole–Cole model) for a rectangular pulse with $f_0 = 6.5$ GHz, $T_b = 10/f_0$.

In Figure 4 the amplitude level of the back scattered field for the transversal plane (2) indicated in Figure 1 is shown. Differences can be observed in the received amplitude level for both the Brillouin (left) and rectangular (center) pulses with respect to the third case (right) for which only the carrier component at f_0 was considered.

In Figures 5–7, the normalized intensity $I(z,t)$ of the electric field $E_T(z,t)$ at any given location (z,t): $I(z,t) = |E_T(z,t)|^2$ [4,17] is plotted. Figure 5 shows the spatial evolution of a Brillouin pulse through a single layer of muscle. It can be seen that the two cycles of the pulse do not overlap.

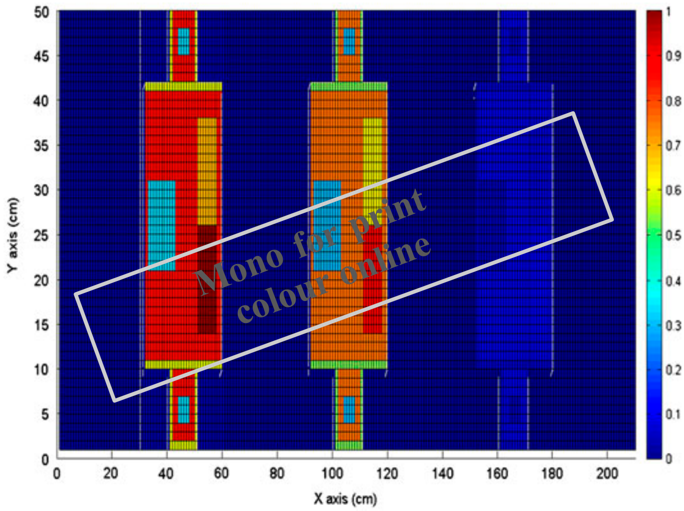

Figure 4. Comparison of peak amplitude levels detected for a backscattered signal for transversal plane at 135 mm for rectangular and Brillouin pulses.

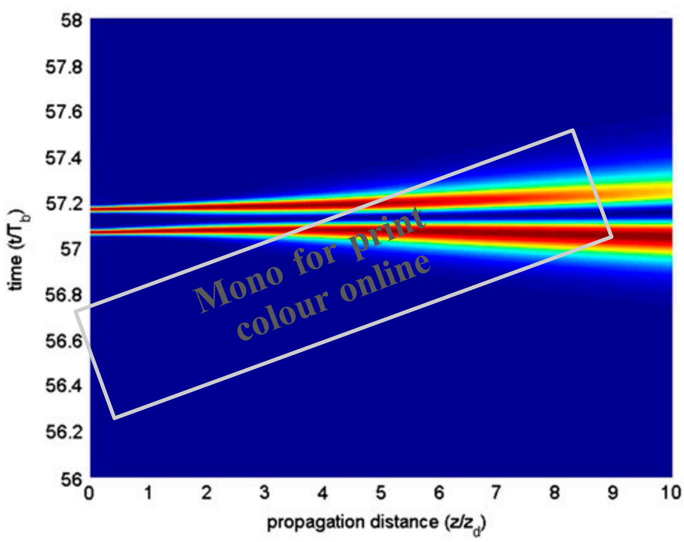

Figure 5. Spatial evolution of the normalized electric field intensity distribution through a dielectric slab of muscle at $f_0 = 6.5$ GHz for a Brillouin pulse BP211.

In Figure 6, the evolution of a rectangular pulse for a slab formed by one layer of skin and one layer of muscle for a rectangular pulse is shown. We observe the large shape distortion, as well as the early extinction of the carrier component. This result is particularly important for intra-body communications. It implies that UWB transmission will be severely affected by the dispersive propagation and robust input signals, and proper spectrum frequency windows must be chosen.

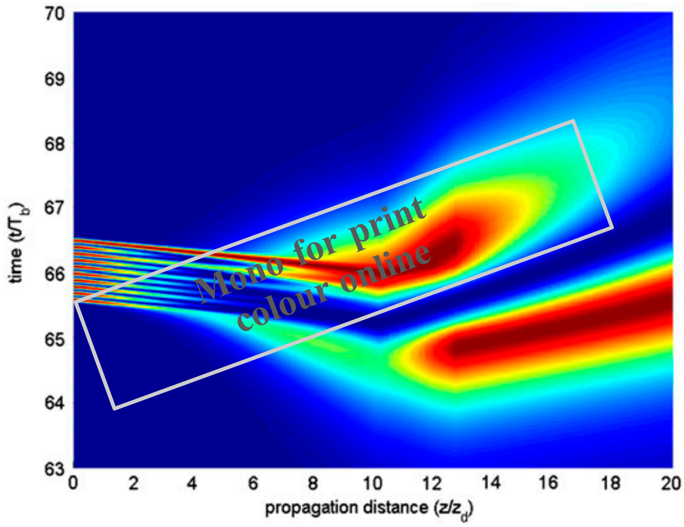

Figure 6. Spatial evolution of the normalized electric field intensity distribution through a dielectric slab formed by skin and muscle for a rectangular pulse at $f_0 = 6.5$ GHz, with $T_b = 10/f_0$.

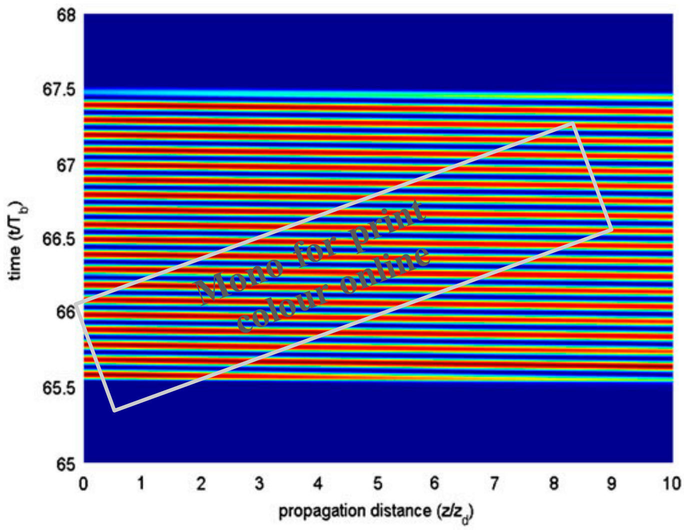

Figure 7. Spatial evolution of the normalized electric field intensity distribution through a dielectric slab formed by skin for a medium-matched rectangular pulse at $f_0 = 6.5$ GHz, with $T_b = 10/f_0$.

4. Conclusions

In this letter, we propose the analysis of the benefits and impairments undergone by a signal transmitted through a dispersive medium, so that a potential application for a given medium can take advantage of precursor formation. This leads to consider dispersive propagation under a totally new perspective that can revolutionize the performance of many actual applications and systems. We have demonstrated the large improvement in terms of SNR for medical imaging, for instance, and these results indicate the likely need to review electromagnetic dosimetry issues. As a future line of work, it is compulsory to analyze the use of precursor in real systems to fully assess the possibility of obtaining benefits from the related advantages (larger propagation, larger level) in order to mitigate and invert the related disadvantages (temporal broadening of the pulse width, carrier frequency oscillation).

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