Conformal Double Exponentially Tapered Slot Antennas (DETSA) for UWB Communications Systems' Front-Ends

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***Abstract*—This paper discusses the use of a Double Exponentially Slot Antenna (DETSA) fabricated on flexible Liquid Crystal Polymer (LCP) as a candidate for Ultra Wide Band (UWB) communications systems. The features of the antenna and the effect of the antenna on a transmitted pulse are investigated. Return loss and E and H plane radiation pattern measurements are presented. The return loss remains below -10 dB and the shape of the radiation pattern remains fairly constant in the whole UWB range (3.1 -10.6 GHz). The main lobe characteristic of the radiation pattern remains stable even when the antenna is significantly conformed. The major effect of the conformation is an increase in the cross polarization component amplitude. The system: transmitter DETSA - channel - receiver DETSA is measured in frequency domain and shows that the antenna adds very little distortion on a transmitted pulse. The distortion remains small even when both transmitter and receiver antennas are folded, although it increases slightly.**

***Index Terms*—Double Exponentially Slot Antenna (DETSA), Liquid Crystal Polymer (LCP), conformal antenna, UWB, ultrashort pulse, distortion**

I. Introduction

The rapid developments in broadband wireless communications and the great number of commercial and military applications necessitate new types of antennas which can support higher bit rates. The Ultra Wide Band (UWB) [1] protocol using the spectrum from 3.1 GHz to 10.6 GHz is a new promising technology suitable for high rate communications in small distances. In this paper, a double exponentially tapered slot antenna (DETSA) on flexible LCP organic material suitable for packaging and integration with other components is introduced and proposed for the UWB range with gain above 7 dBi and return loss below -10 dB for the whole frequency range. The DETSA is a variation of the Vivaldi antenna, with the outer edge exponentially tapered, and it was introduced for the first time in [2] with design and performance characteristics discussed in [3] and [4]. A coplanar waveguide – fed version of DETSA is explored in [5] for a UWB sub-band, while in [6] a Vivaldi antenna is proposed for the ultra wide band. For the quality of the received pulse time domain measurements can be used [7]-[8] but in the present work we use a frequency domain measurement to estimate the distortion caused by the DETSA .

II. Antenna Design

The proposed antenna was fabricated on a 200 μm thick Liquid Crystal Polymer (LCP) substrate with an 18 μm thick copper layer. The DETSA schematic is presented in Fig. 1. The length of the board is L=13.62 cm, the width is D=6.64 cm, and the slot gap at the feeding point is 100 μm wide. LCP was preferred because of a number of desirable features. The dielectric constant ε_r=3.1 is low enough to be used for an end-fire antenna, it has low loss (tanδ=0.002) while being conformal, and it is easy to fabricate with an engineered Coefficient of Thermal Expansion (CTE) [9]. Standard photolithography was used for the fabrication. The design dimensions have been optimized for the antenna to be matched over a frequency range of 3 GHz to 11 GHz.

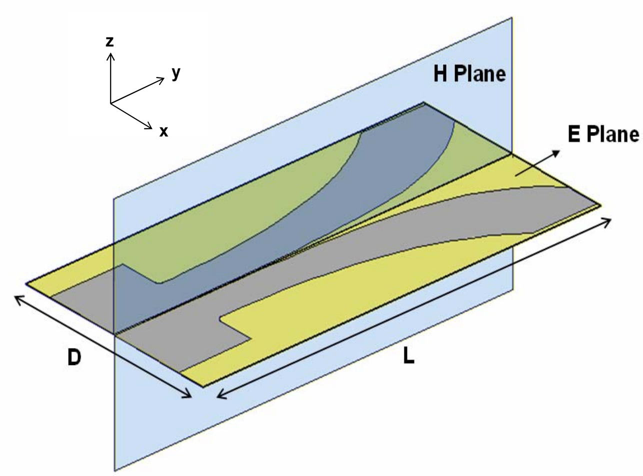

Fig. 1. DETSA schematic. E and H planes are defined

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III. RETURN LOSS AND RADIATION PATTERN MEASUREMENTS

A. Return loss measurement

For return loss and radiation pattern measurements, an SMA connector was soldered directly on the slot with no tuning components. The contour that describes the projection of the folded antenna surface on the H plane is given by (1) where x is measured in cm. The antenna was attached on a piece of styrofoam with the same curvature to provide mechanical support and stability.

$$C(x) = 0.048 + 1.010x - 0.121x^2 + 0.004x^3 \quad 0 \le x \le 12.5 \qquad (1)$$

The simulated and measured return loss is presented in Fig. 2, where it can be seen that good agreement is achieved between simulated and measured return loss, that there is no difference between flat and folded, conformal, antenna return loss, and the return loss remains below -10 dB in the whole UWB range. The observed "saw" pattern is expected because DETSA is a traveling wave antenna, not a resonance radiation element. For the frequencies in the 8 GHz to 10.6 GHz range the return loss is below -15 dB. In those frequencies relatively higher gain is measured. The planar and folded antennas are shown in Figs 3 and 4 respectively.

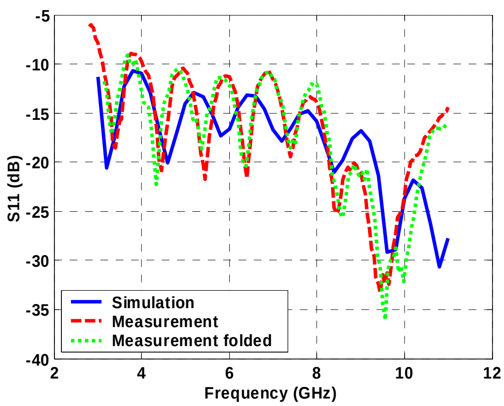

Fig. 2. Return loss simulation and measurement for planar and folded antenna.

B. Radiation pattern measurements

The far field radiation pattern measurements were performed in the E and H planes defined in Fig. 1 with the directivity direction being the intersection of the two planes. To experimentally characterize experimentally the DETSA antenna, it is sandwiched between two ½ inch thick styrofoam pieces to give it enough mechanical stability for the measurements. The antenna is tested in a far-field range with the DETSA as the receive antenna, and a 2 to 18 GHz, ridged-rectangular horn antenna with a gain of 6 dB at 2 GHz and 12 dB at 18 GHz is used as the transmitting antenna. After experimentally determining the transmitted power to maximize the detector sensitivity without saturating it, the system is calibrated. The rotary stage and the detector voltage recording from the lock-in amplifier are automated.

The main problem with wideband antennas is the electrical length variation with frequency, which causes significant distortion in the radiation patterns. Generally the increase in frequency in end-fire antennas causes the main beam to become narrower (reduced beamwidth) and the directivity to increase. The y axis in Fig.1 corresponds to $\varphi=90^o$ for the E plane cuts and to $\theta=90^o$ for the H plane cuts. x axis corresponds to $\varphi=0^o$ and z axis to $\theta=0^o$. For the folded antenna, the x-z plane is located at the SMA connector and the y axis is along the direction of the SMA adapter. Thus, while E and H plane cut definitions do not change, the DETSA antenna is not in the x-y plane as shown in Fig. 1.

Normalized radiation patterns at 6 GHz, close to the band center are presented. Co and cross polarization for planar and folded antennas are presented in Figs 5 and 6 respectively. The H plane beam is slightly wider and with fewer side lobes compared to the E plane beam at this frequency. There is a small asymmetry in the folded antenna pattern which is due to the cable direction which was not aligned with the directivity direction as it was for the planar antenna measurement. Generally though, the shape of the beam does not present great variations. The cross-polarization level for the planar antenna is below -20 dB, and it is below -10 dB for the folded antenna. This 10 dB increase in cross-polarization E field magnitude is the major effect caused by folding. The main beam characteristic of the radiation pattern remains unchanged as the frequency increases. This is a major advantage of this antenna, with respect to competitive UWB designs [10]-[11] for which the shape of the beam changes significantly while the frequency increases. The gain at 6 GHz is measured at 9.8 dBi.

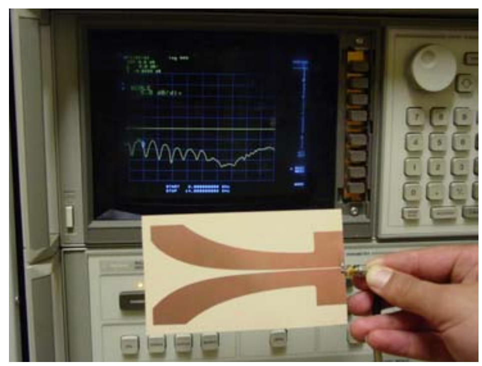

Fig. 3. Planar DETSA antenna connected to the HP 8530A Network Analyzer

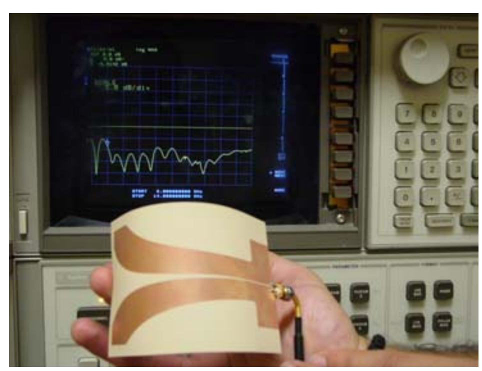

Fig. 4. Folded DETSA antenna connected to the HP 8530A Network Analyzer

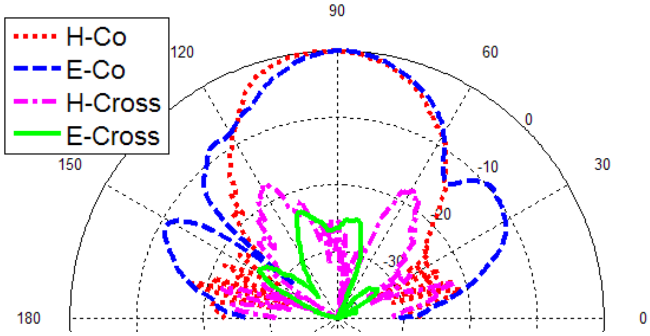

Fig. 5. E and H plane far field measurements for the planar DETSA. Both co and cross polarization are presented.

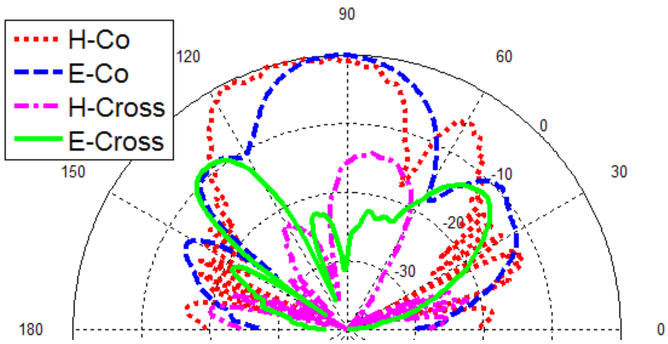

Fig. 6. E and H plane far field measurements for the folded DETSA. Both co and cross polarization are presented.

IV. FREQUENCY DOMAIN MEASUREMENT FOR DISTORTION ESTIMATION

A. Setup

To get an estimate of the effect of the antenna on a transmitted pulse, the setup in Fig. 7 was used. Two antennas are used, one as a transmitter and the second as a receiver. The two DETSA antennas are aligned for optimum reception and the distance between them is set at 1.5 m. The minimum far field distance given from $R=D^2/\lambda$ is calculated at 0.65 m when D=13.6 cm and λ for 10.6 GHz are used. Both antennas are connected to an HP 8530A network analyzer and S_{21} measurement is taken. The antennas' planes are kept perpendicular to the ground as they appear in Fig. 3 to avoid the use of mechanical support with styrofoam. The measurement is repeated when both the antennas are identically conformed. The whole process takes place in a laboratory environment that resembles an actual communications environment more realistically compared to a potential measurement in an anechoic chamber. The measurements are presented in Fig. 8 for both planar and folded antennas. The misalignment, as a result of the folding, causes higher fading for the higher frequencies (8-10.6 GHz) due to the respective higher directivity.

B. Distortion estimation

The S_{21} measurement represents the transfer function H(f) of a "black box" that consists of the transmitter DETSA the 1.5 m laboratory environment channel and the receiver DETSA. Any time domain pulse s(t) to be transmitted has a Fourier transform S(f). The pulse detected at the receiver has a Fourier transform R(f)=S(f)H(f). The transmitted pulse s(t) and the received pulse $r(t)=F^{-1}\{R(f)\}$ are correlated to get an estimation of the distortion added by the DETSA UWB communications system. The distance between the two antennas is long enough to guarantee a far field measurement and at the same time, small enough that is reasonable to assume that distortion of the early response by channel can be neglected.

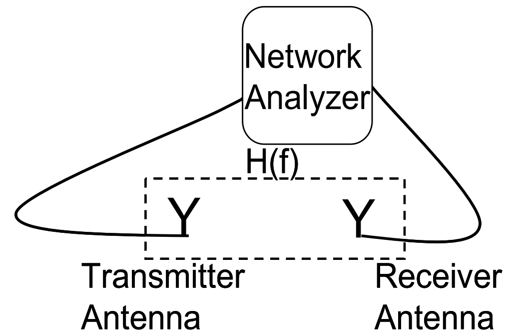

Fig. 7. Setup for the system: transmitter - channel – receiver, frequency domain measurement.

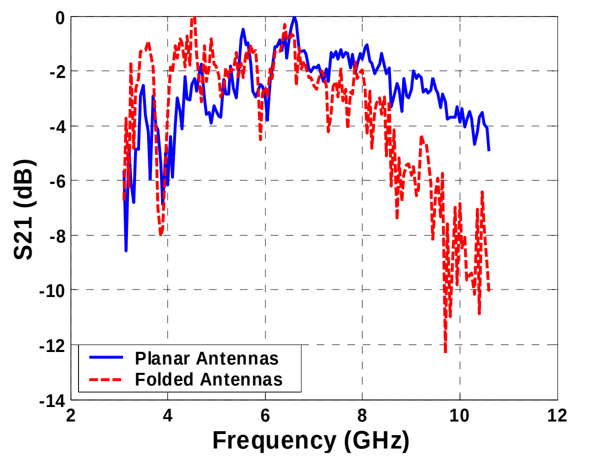

Fig. 8. S_{21} measurements for the system: transmitter - channel – receiver.

We investigate the effect on an ideal rectangular pulse of duration of 1 nanosecond. The spectrum for a rectangular pulse is infinite. We compare the received pulse with the equivalent time domain pulse that is created when the infinite baseband spectrum is modulated at (6.65=(10.6-3.1)/2) GHz and filtered from an ideal passband filter with passband range at 3.1-10.6 GHz. The superimposed pulses are presented in Fig. 9 and very good agreement is observed. The folded antennas cause stronger distortion than the planer antennas but still the maximum correlation value, estimated with function (2), results in 0.96 for the folded antennas and 0.99 for the planar antennas.

$$Corr(d)=\frac{\sum_i\left[\left(x(i)-m_x\right)\left(y(i-d)-m_y\right)\right]}{\sqrt{\sum_i(x(i)-m_x)^2}\sqrt{\sum_i(y(i)-m_y)^2}} \qquad (2)$$

x(i) and y(i) are the compared waveforms, m_x and m_y are the respected mean values.

The rectangular pulse is an ideal pulse and is not used in practice for any communication systems because of the huge spectrum required. Therefore we use a raised cosine pulse to investigate the same effect. The raised cosine pulse has a spectrum (3) that causes zero intersymbol interference (ISI) and is a popular pulse for several modulations. The time domain pulse as a result of the spectrum described by (3) is given by (4):

$$H_{rc}=\begin{cases} Ts & 0\le|f|\le(1-a)/2Ts \\ \frac{Ts}{2}\left[1-\sin\frac{\pi Ts}{a}\left(|f|-\frac{Ts}{2}\right)\right] & (1-a)/2Ts\le|f|\le(1+a)/2Ts \\ 0 & (1+a)/2Ts\le|f| \end{cases} \quad (3)$$

$$s_{RC}=F^{-1}\{H_{RC}(f)\}=\frac{\sin\pi t/\mathrm{Ts}}{\pi t/\mathrm{Ts}}\frac{\cos a\pi t/Ts}{1-4a^2t^2/Ts^2} \quad (4)$$

For the pulse presented in Fig. 9 Ts = 1/BW was used, where BW=(10.6 – 3.1) GHz and the roll-off factor is a=0.5. The pulse described from the analytical expression (4) is plotted with the normalized inverse Fourier transform of the pulse's spectrum multiplied by the measured H(f) and very good agreement is deduced (Fig. 10). The maximum correlation value is estimated at 0.98 for the planar antennas and 0.95 for the folded antennas.

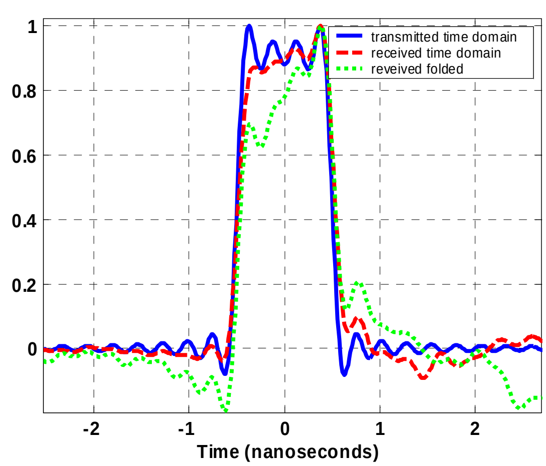

Fig. 9. Time domain rectangular pulse. The solid line pulse is a rectangular pulse with 7.5 (10.6-3.1) GHz bandwidth that is used as a transmitted pulse. The duration of the pulse is only 1 nanosecond. Small distortion is added by the system: transmitter – channel – receiver.

The measurement and the mathematical analysis of the data clearly indicate that very little distortion is introduced by the antennas, and the antennas practically do not affect in a destructive way the transmitted pulses. This is mainly due to their broadband performance (3.1-10.6 GHz) and high directivity.

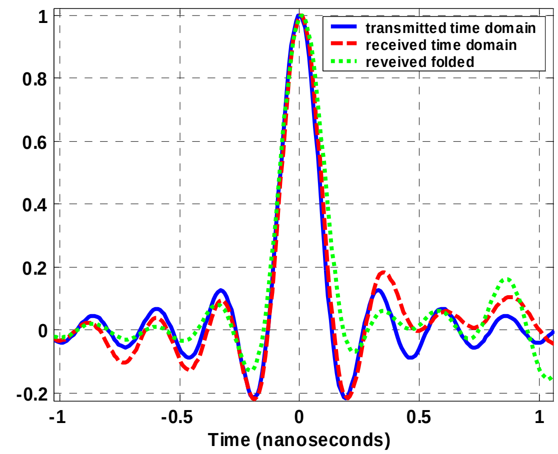

Fig. 10. Time domain pulse described by (4) superimposed with distorted pulse from both planar and folded antennas. The pulse has theoretically infinite duration because of the confined spectrum but it decays with 1/t.

V. Conclusion

A DETSA on flexible organic material (LCP), suitable for conformal packaging and integration with other components, is introduced and proposed for the UWB range. The measurements agree fairly well with the simulations and this antenna is proved to perform well in the whole UWB range. Return loss below -10 dB is measured for the whole frequency range of operation both when the antenna remains planar and when is folded. The antenna performs with high gain starting from 7 dBi for low frequencies and up to 12 dBi for the higher frequencies. Frequency domain measurements indicate that the antenna, when is planar or even when is significantly folded causes minimum distortion to any transmitted pulse. The antenna on LCP is conformal, can be easily fabricated with relatively low cost and is a good candidate for a number of UWB applications.

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