Wideband ultralow reverberation antenna for biological sensing

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A wideband bow-tie antenna has been designed using the finite-difference time-domain (FDTD) method. When positioned at the surface of a biological tissue half-space, the calculated reflections from the antenna ends are 106dB below the exciting pulse. This facilitates detection of local weakly-scattering tissue structures.

Video pulse radars operating at the air-earth interface have been used to detect buried structures such as pipes, cables and mines [1]. Versions of these radars operating at the surface of the human body were proposed as means of detecting and possibly imaging internal biological tissues [2]. The use of electromagnetic waves in this manner has several advantages over X-rays: eliminating tissue exposure to ionising radiation and obtaining relatively large tissue contrasts according to their water content. However, a problem arises in that small or weakly-scattering tissue structures adjacent to an impulsively excited antenna can be obscured by the reflections from the ends of the antenna. (Early-time reflection due to impedance mismatch between the source cable and the antenna is assumed to be fully decayed before the end reflections.) For the case of free-space radiation of ultra-wideband video pulses, resistively-loaded conical and bow-tie antennas have been reported [3, 4] having end reflections 40–50dB below the exciting pulse. This reflection level is almost certainly too high for detecting local embedded biological tissue structures in the range 2–5cm below the surface because of strong electromagnetic wave absorption in the surrounding tissues.

In this Letter, we report the design of a wideband bow-tie antenna suitable for biological sensing applications. The design procedure uses three-dimensional finite-difference time-domain (FDTD) simulations [5-7] in the manner of [3, 4, 8]. In fact, the design is based on a modification of the continuous resistive loading examined in [3, 4] in combination with the use of a zero-DC Gaussian-pulse modulated carrier excitation and the location of the antenna at the interface of the biological tissue half-space.

Consider the bow-tie antenna and tissue half-space geometry of Fig. 1. The antenna is composed of a material that has the following sheet resistance:

$$R(z) = R_0 \frac{1 + (R_{1/2}/R_0 - 2)(z/h)}{1 - z/h} \quad \Omega/\square \tag{1}$$

where $R_0 = 3.5 \times 10^{-5} \,\Omega/\Box$, $R_{1/2} = 110 \,\Omega/\Box$, and z/h is the normalised axial distance along the bow tie for $h = 4 \,\mathrm{cm}$. R_0 is determined by the choice of the metal used at the feed point. $R_{1/2}$ is chosen to give the desired level of suppression of the reflected pulse. The taper is a modification of that used in [4]. Here, R is a function of the axial distance z from the centre of the bow tie, rather than a function of the radial distance. Also, $R(z=0)=R_0$ in our design so that the conductivity at the centre of the bow tie is large but finite. At the ends of the bow-tie antenna (z=h) the conductivity goes to zero.

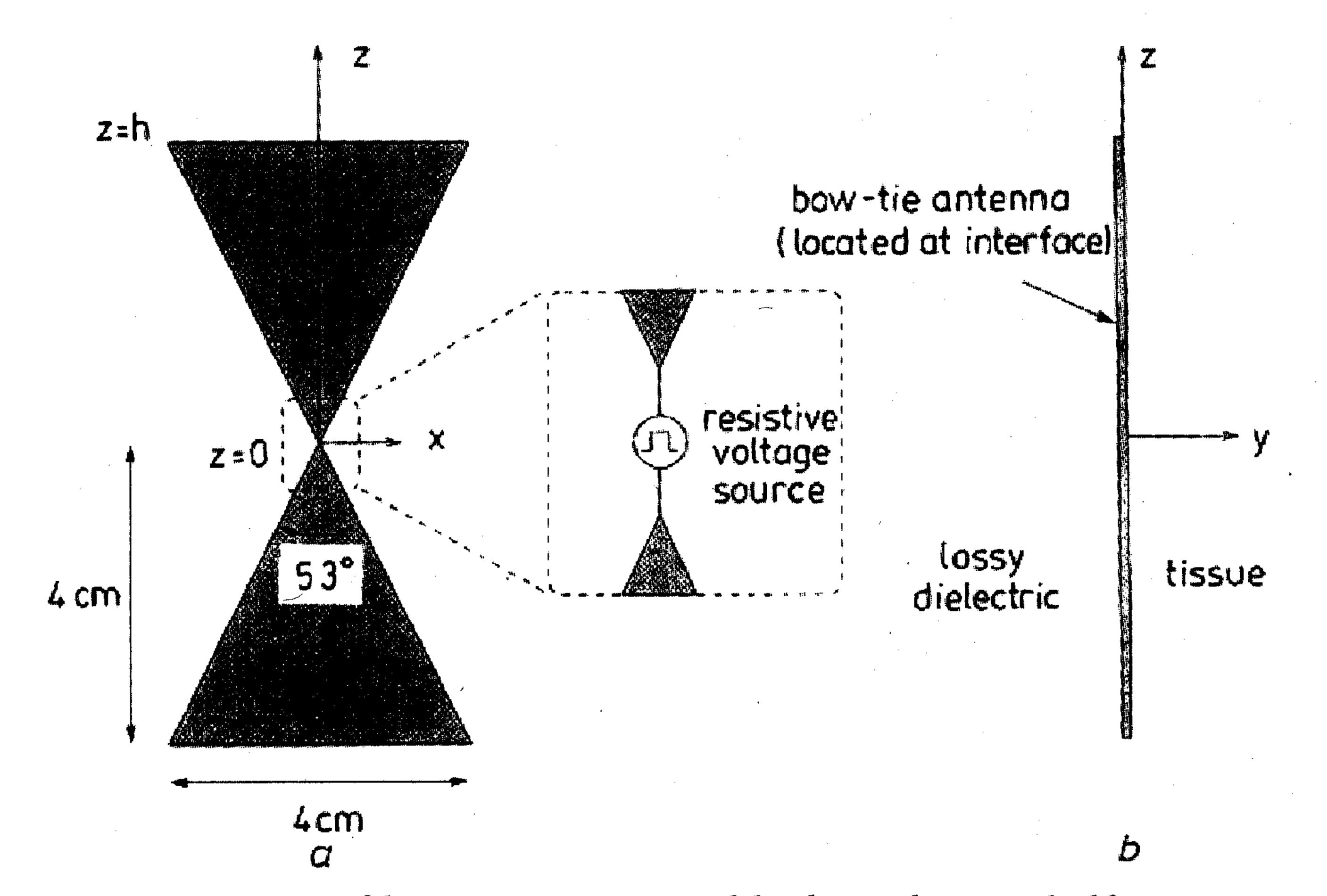


Fig. 1 Geometry of bow-tie antenna and biological tissue half-space a Plan view, showing the resistive-voltage-source feed as an inset b Side view

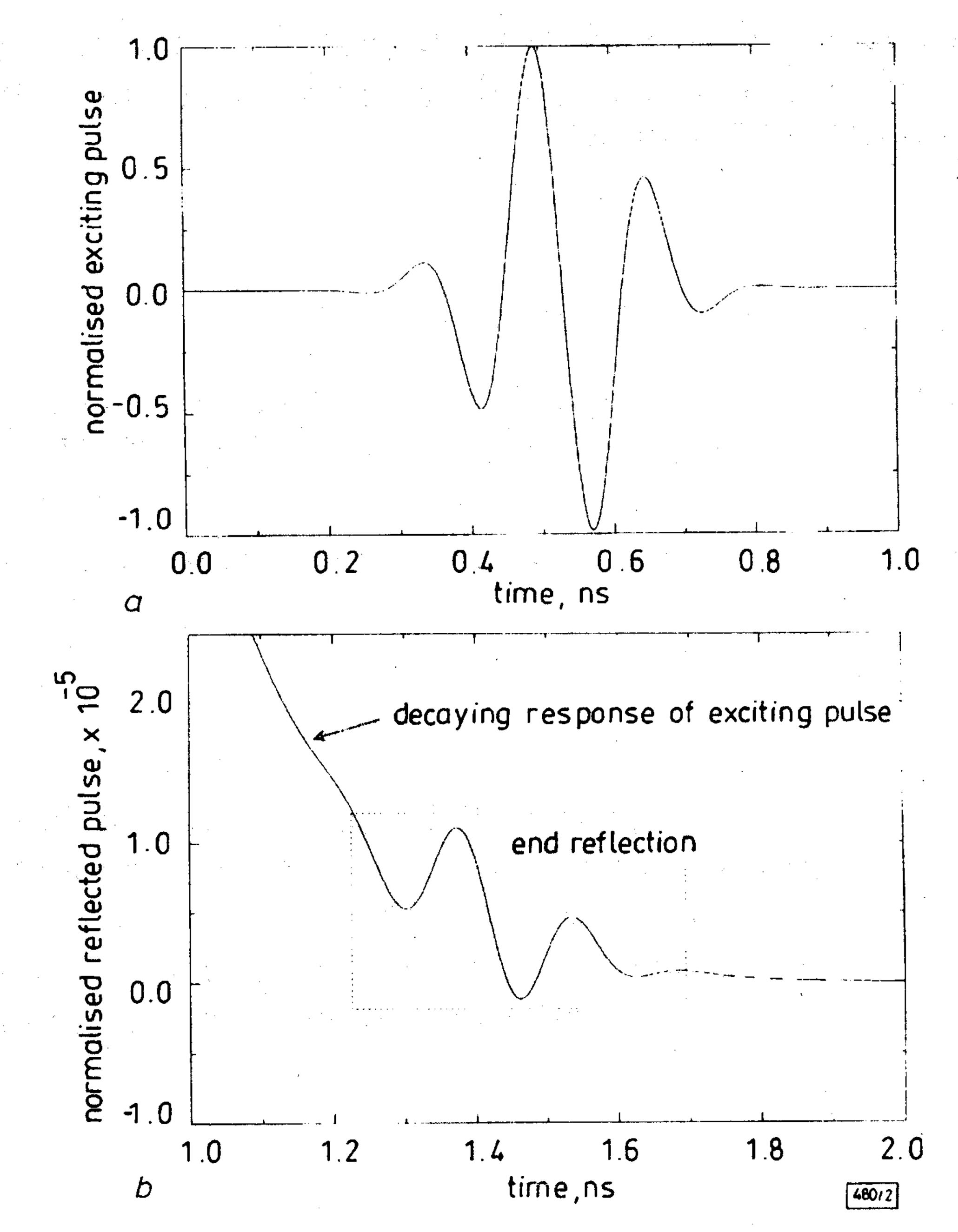


Fig. 2 FDTD computed time responses

- a Early time response showing normalised exciting pulse as observed at feed point of bow-tie antenna
- b Later time response showing normalised end reflection at feed point

The antenna is assumed to be embedded within a large block of lossy dielectric material that matches the dielectric parameters of the underlying tissue half-space. In this example, the biological half-space is composed of a fat-like tissue for which $\epsilon_r = 9$ and $\sigma = 0.4$ S/m. Excitation to the antenna is provided by a 50 Ω resistive source [9] having the following time dependence:

$$V(t) = V_0 \sin[2\pi f(t - t_0)]e^{-[(t - t_0)/\tau]^2}$$
 V (2)

where f = 6GHz, $\tau = 0.133$ ns, and $t_0 = 4\tau$. This pulse has a temporal width of 0.22ns (full width at half maximum, FWHM), an amplitude spectral width of 4GHz (FWHM), and zero DC content. Although very wideband, this excitation differs significantly from that used in [3, 4]. Here, the excitation spectrum is a bandpass Gaussian function (centred about 6GHz) which nulls the low-frequency energy and minimises the resulting exponential field decay in the surrounding lossy medium.

Fig. 2a and b plot, respectively, the FDTD-computed exciting pulse and reflection from the antenna ends as observed at the feed point. The vertical scales in these Figures have been normalised to the peak value of the exciting pulse. The power ratio in decibels is obtained by taking $20 \times$ the logarithm of one-half of the peak-topeak amplitude of the normalised end reflection of Fig. 2b. The end reflection is seen to be at -106dB relative to the exciting pulse. This level is 60dB lower than the end reflections calculated using FDTD and is confirmed by measurements for the video-pulseexcitation free-space cases of [3, 4]. It is apparent, but unexpected, that the lossy nature of the medium surrounding the bow-tie antenna acts in concert with its resistive loading and the bandpass nature of the excitation to reduce the antenna reverberation by six orders of magnitude. Further, the resistive loading causes little loss of radiating efficiency for the electric fields penetrating the tissue half-space. At 1 cm deep into the tissue below the feed point, the calculated field is reduced by only 0.25dB relative to the all-metal antenna simulation. We have found that suppression of the end reflection to $-90 \,\mathrm{dB}$ or better is possible for a wide range of the $R_{1/2}$ parameter of the antenna sheet resistance, and is quite insensitive to the nature of the lossy tissue medium.

Preliminary FDTD studies indicate that an antenna reverberation dynamic range exceeding 100dB in combination with bandpass detection of a scattered pulse via a matched filter (matched relative to the antenna excitation at its driving point) is sufficient to permit monostatic sensing of small or weak tissue anomalies at least several centimetres below the surface. This is a very useful detection range for a number of important biomedical applications of current interest.

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