Transient Light Waveguides Deep Into Scattering Media by Transversal Ultrasound

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Abstract: We present the concept of ultrasound-induced light waveguides based on transient ultrasound waves to partially offset strong light scattering. The extent and configuration of such waveguides is fundamentally limited only by ultrasound propagation losses.

Recently, a few concepts were introduced to perform light waveguiding in a scattering medium by transversal ultrasound fields. So far these concepts are based on US waves, induced in a cylindrical cavity, either formed by cylinder-shaped transducer [1–3], or nonlinear photoacoustic waves [4]. Such arrangement limits the extents to which the US light waveguiding could be applied to biomedical objects *in vivo*, since the circumference of the active volume is limited and acoustic load on the object might be high.

To achieve an ultrasound guided low-loss light delivery without the above mentioned drawbacks, we investigate the usage of transient ultrasound (US) waves. Although the waveguide is active during a very limited period of time, we were able to deliver light into scattering media with properties close to that of low scattering real tissues [5]. The concept of transient ultrasound light waveguiding (TULW) is schematically depicted in **Fig. 1**.

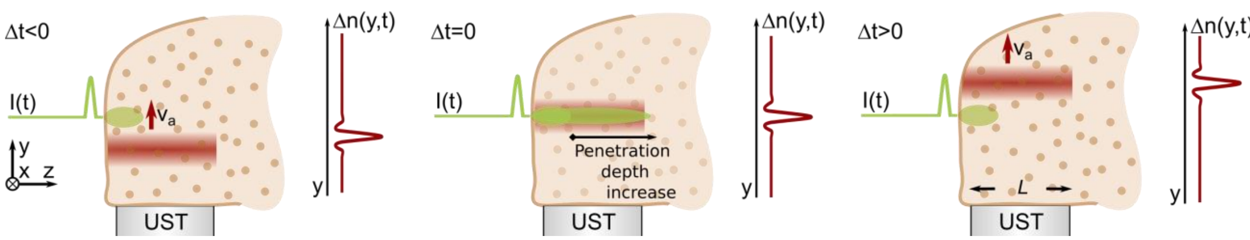

Figure 1 – transient ultrasound wave dynamically changes the refractive index of the medium, allowing the refractive index perturbation to guide a correctly timed light pulse deeper into a scattering medium

The traveling US wave modulates the refractive index of the base material proportionally to the local pressure *p* [6,7]. Then, for a single frequency (f_a) sine burst and a sufficiently short light pulse the refractive index change is given as $\Delta n(y) = \gamma\, p \sin(2\pi\lambda_a/f_a + \varphi)$, where γ – is the piezo-optic coefficient of water (γ=1.2…1.5·10^{-10} Pa^{-1} [6,7]), λ_a – is the US wavelength in the medium (λ_a =710 µm for f_a=2.09 MHz in water with v_a=1482 m/s), and φ – is the phase delay under 2π, which is dependent on the synchronization between the US pulse and the light pulse (Δt). Therefore, a transient US wave forms a dynamic US-induced refractive index structure (US-IRIS), traveling along the medium with US speed v_a. Consecutively, US-IRIS could be described as a dynamic gradient index medium (GRIN) [8,9].

If the US-IRIS is launched transversally to the light propagation direction, light propagation is manipulated when the synchronization condition is fulfilled. Such GRIN structures are known for light focusing and waveguiding capabilities, and, by extension, a transient US-IRIS shall possess these capabilities as well. To investigate their properties, transmission experiments are performed, using a gated camera and a fiber-based point detector to perform 3D light intensity sampling in a manner, compatible with later usage with liquid scattering phantoms [10].

As illustrated in **Fig. 2**, US-induced refractive index gradients are indeed capable of a 2D light focusing in a clear medium, leading to the light intensity redistribution in the US-IRIS focal plane.

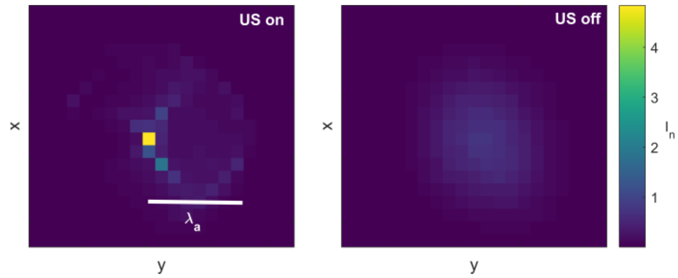

Figure 2 - transient US-induced refractive index structure focuses synchronized light pulse in water. (left) US-IRIS is present in light propagation volume, (right) US is switched off

Further experiments were carried out in Intralipid-20% (IL) dilutions with volume concentrations of 0.5%, 1%, and 1.5%, chosen to provide lower boundary estimated μ_s` of 1.5/cm, 3/cm and 4.5/cm at the wavelength of 532 nm, respectively. The 3D light intensity assessment is performed using fiber-probe raster scanning to confirm lateral restriction of the light intensity increase, and thus prove light waveguiding by TULW.

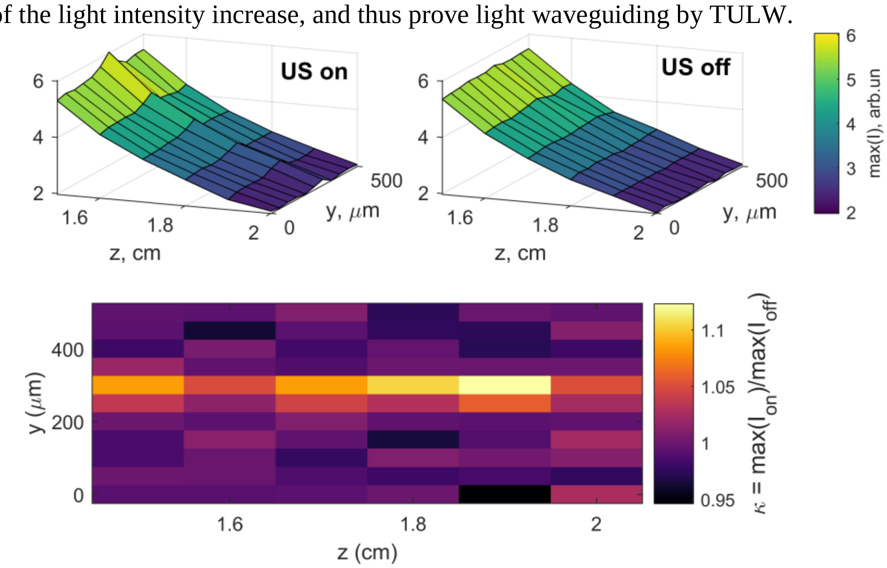

Figure 3 - transient ultrasound waveguiding leads to the intensity increase up to the depths of 2 cm in a scattering phantom with estimated reduced scattering coefficient μ_s` of 4.5/cm

As shown in **Fig. 3**, TULW provides light intensity increase up to the depths of 2 cm in the IL-based phantoms with μ_s` of 4.5/cm, corresponding to the optical thickness of 90 mean free paths. This intensity increase is restricted laterally, hence, light waveguiding deep into scattering media by TULW is confirmed.

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