Analog time-reversed ultrasonically encoded light focusing inside scattering media with a 33,000× optical power gain

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Supplementary note

Signal-to-noise ratio (SNR) of optical detection

If the incident optical illumination generates an average photocurrent $\bar{i}_s$, the amplitude SNR of the photodetector output is[29]

$$SNR = \frac{\bar{i}_s}{\sqrt{\left[2e\bar{i}_s + 2e\bar{i}_b + \frac{4k_B T}{R_L}\right]\Delta\nu}}, \tag{S1}$$

where e is the elementary charge, $\bar{i}_b$ is the average reverse bias leakage current, k_B is the Boltzmann constant, T is the absolute temperature, R_L is the load resistance and $\Delta\nu$ is the bandwidth of the detector. The three terms on the denominator account for the signal shot noise, dark-current shot noise, and thermal noise.

A pulse with a duration τ_p has a bandwidth of $\Delta\nu \approx 1/(2\tau_p)$. Denoting the pulse energy as E_p, the bandwidth can be expressed in terms of E_p as

$$\Delta\nu = \frac{\bar{i}_s}{2E_p\rho_d}, \tag{S2}$$

where ρ_{d} denotes the photodetector's responsivity. Inserting Eq. (S2) in (S1) we get

$$SNR = \sqrt{\frac{E_{\mathrm{p}}}{\frac{\alpha}{\overline{P}} + \beta}}\,. \tag{S3}$$

In Eq. (S3), $\alpha = \left(e\overline{i_{\mathrm{b}}} + 2k_{\mathrm{B}}T / R_{\mathrm{L}}\right) \Big/ \rho_{\mathrm{d}}^2$ and $\beta = e / \rho_{\mathrm{d}}$ are constants, and $\overline{P}$ denotes the average power of the pulse ($E_{\mathrm{p}} \big/ \tau_{\mathrm{p}}$).

Reference

29 Yariv, A. & Yeh, P. *Photonics: Optical Electronics in Modern Communications (The Oxford Series in Electrical and Computer Engineering).* (Oxford University Press, Inc., 2006).

Supplementary figure

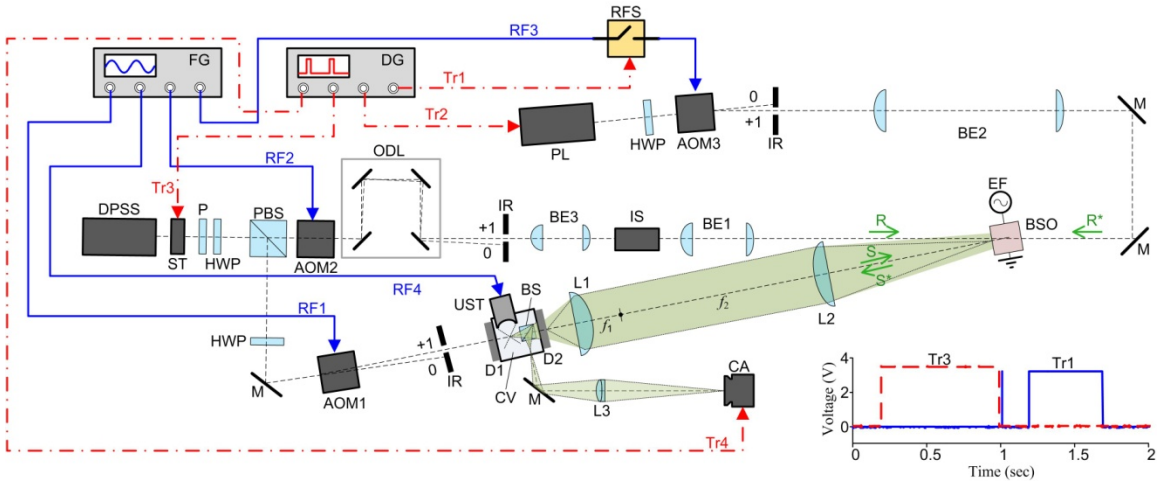

Figure S1. System setup. AOM, acousto-optic modulator; BE, beam expander; BS, 50:50 non-polarizing beamsplitter; BSO, $Bi_{12}SiO_{20}$ crystal; CA, CMOS camera or photodiode; CV, water-containing cuvette; D, diffuser; DG, delay generator; DPSS, diode-pumped solid-state laser; EF, externally applied field; FG, function generator; HWP, half-wave plate; IR, iris; IS, optical isolator; L, lens; M, mirror; ODL, optical delay line; P, optical polarizer; PBS, polarizing beamsplitter; PL, pulsed laser; RF, radio-frequency driving signal; RFS, radio-frequency switch; ST, optical shutter; Tr, trigger signal; UST, ultrasonic transducer. Inset: oscilloscope traces of Tr1 and Tr3.