FIBRE-OPTIC HYDROPHONES FOR HIGH-INTENSITY ULTRASOUND DETECTION: MODELLING AND MEASUREMENT STUDY

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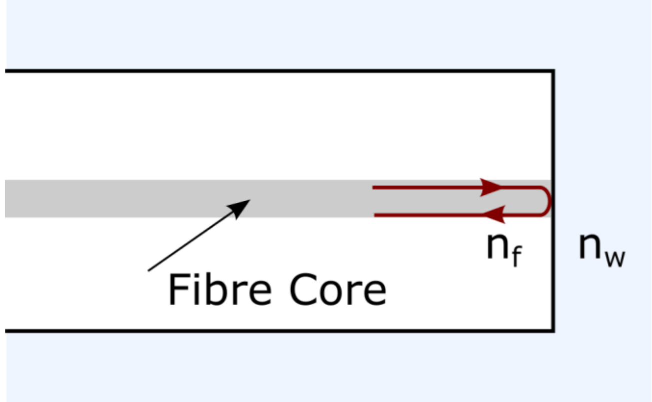
INTRODUCTION- FIBRE OPTIC HYDROPHONES (FOHs)

Uncoated FOH (Fresnel Reflection Hydrophone)



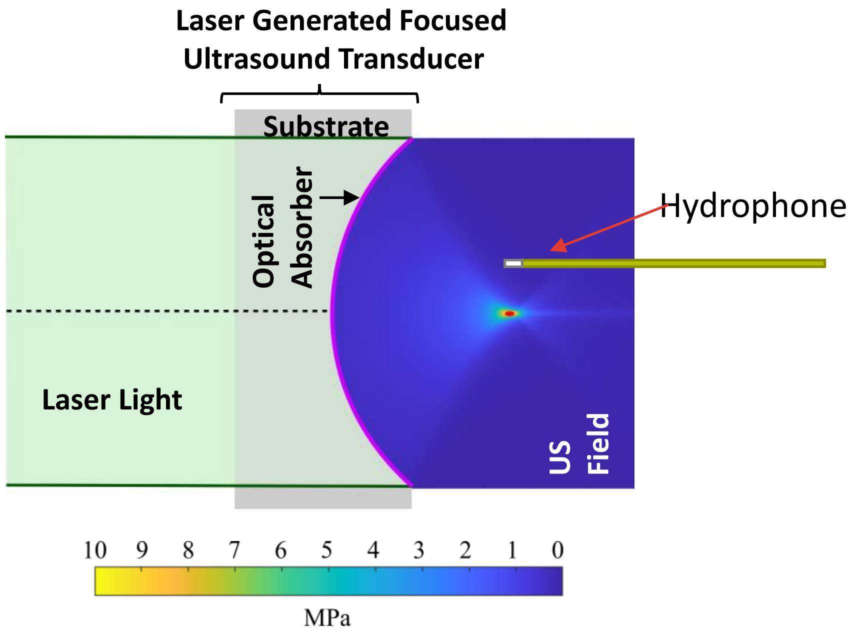
Schematic of an uncoated FOH
n_f= refractive index of fibre,
n_w= refractive index of water

Key Advantages:

- Robust
- Small sensitive region (large bandwidth)

Critical Disadvantages:

- Low signal-to-noise ratio (SNR)
- Challenging field characterization

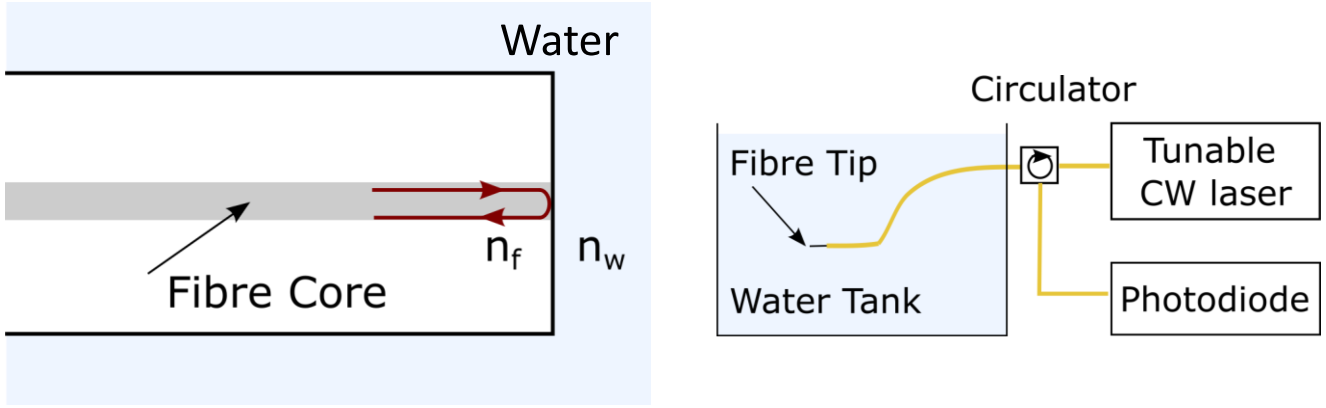


P_0max (at surface)=1 MPa
Centre Frequency=10 MHz
Peak Positive Pressure (at focus)=11 MPa

Aytac-Kipergil, E., et al. (2021). Modelling and measurement of laser-generated focused ultrasound: Can interventional transducers achieve therapeutic effects?. *The Journal of the Acoustical Society of America*, *149*(4), 2732-2742.

INTRODUCTION-FIBRE OPTIC HYDROPHONES (FOHs)

Working Principe of an Uncoated FOH



The variation of refractive index of the fluid with pressure change

$$\text{Reflectance} = \frac{(nf - nw(P))^2}{(nf + nw(P))^2}$$

$$\text{Sensitivity} = \frac{V_{dc}}{(R+\alpha)}\left|\frac{dR}{dP}\right|$$

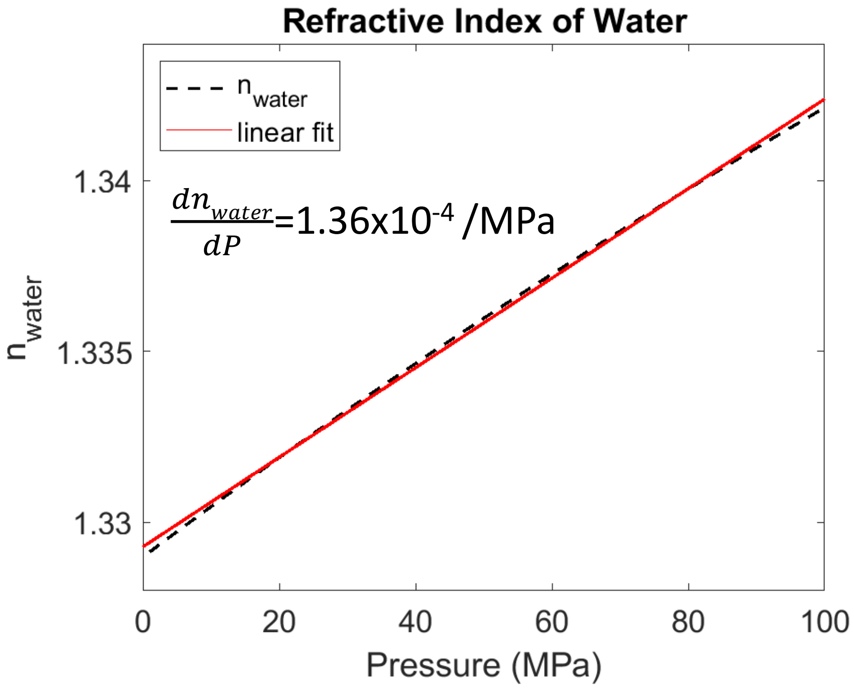
V_{dc}=Baseline DC voltage, R=Reflectance, P=Pressure, α= Light scattering factor.

Smith N. *et al.*, 2012

Refractive Index Change with Pressure

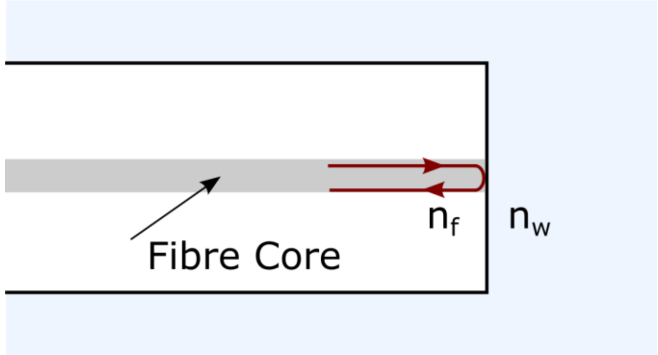
$$n_{water,P} = 1 + (n_{water,0} - 1)\left(1 + \frac{P-P0}{P0+295.5}\right)^{\frac{1}{7.44}}$$

Wurster C. *et al.*, 1994



INTRODUCTION- FIBRE OPTIC HYDROPHONES (FOHs)

Uncoated FOH

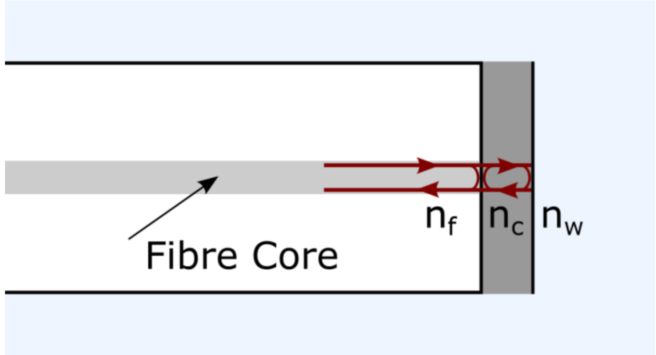


1) **The variation of refractive index of the fluid with pressure change**

Disadvantages: Low SNR, challenging ultrasound characterization

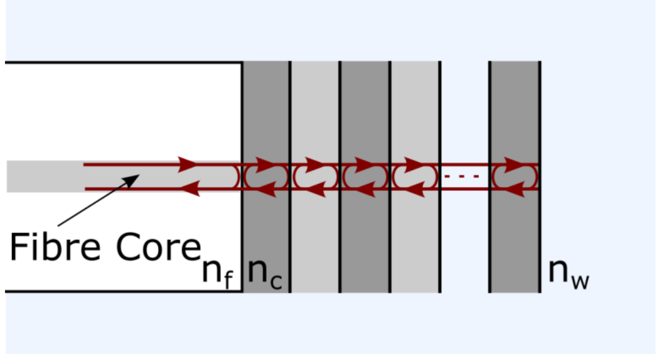
Wilkens, V., and Ch. Koch, 1999

Single-layer coated FOH



1) The change in optical thickness of the coating with pressure change
2) The variation of the refractive index of the coating with pressure change
3) **The variation of refractive index of the fluid with pressure change**

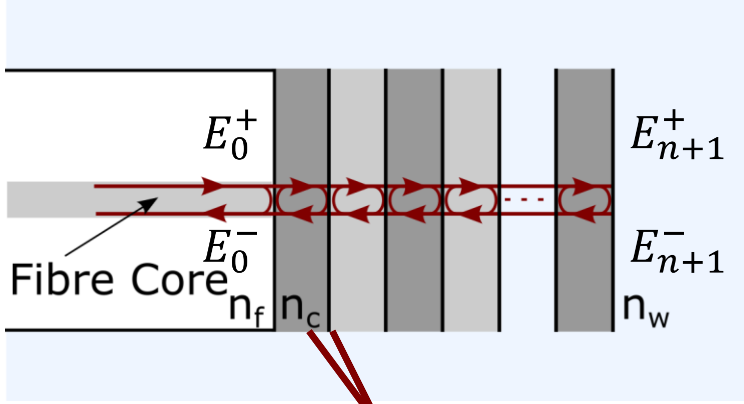
Multi-layer coated FOH



1) **The change in optical thickness of the coating with pressure change >5 layers**
2) The variation of the refractive index of the coating with pressure change
3) The variation of refractive index of the fluid with pressure change

The aim is to increase SNR while withstanding high-intensity pressures.

METHODS - SIMULATION MODEL- GENERAL TRANSFER MATRIX METHOD



D: Dynamic matrix
P: Propagation matrix.

Katsidis, C. C. *et al.*, 2002

$$\begin{pmatrix}E_0^+\\E_0^-\end{pmatrix} = \underbrace{D_0^{-1}\left[\prod_{c=1}^{n} D_c P_c D_c^{-1}\right] D_n}_{\text{Transfer Matrix, T}} \begin{pmatrix}E_{n+1}^+\\E_{n+1}^-\end{pmatrix}$$

$$\begin{pmatrix}E_0^+\\E_0^-\end{pmatrix} = \begin{bmatrix}T_{11} & T_{12}\\T_{21} & T_{22}\end{bmatrix}\begin{pmatrix}E_{n+1}^+\\E_{n+1}^-\end{pmatrix}$$

$R(P)=|(T_{21}/T_{11})|^2$ → dR/dP

1) The change in optical thickness of the coating with pressure change

$$\Delta d_c = -\frac{\Delta P_c}{\rho_c \nu_c} d_c$$

2) The variation of the refractive index of the coating with pressure change

$$\Delta n_c \approx \frac{0.3\,\Delta P_c}{\rho_c {\nu_c}^2}$$

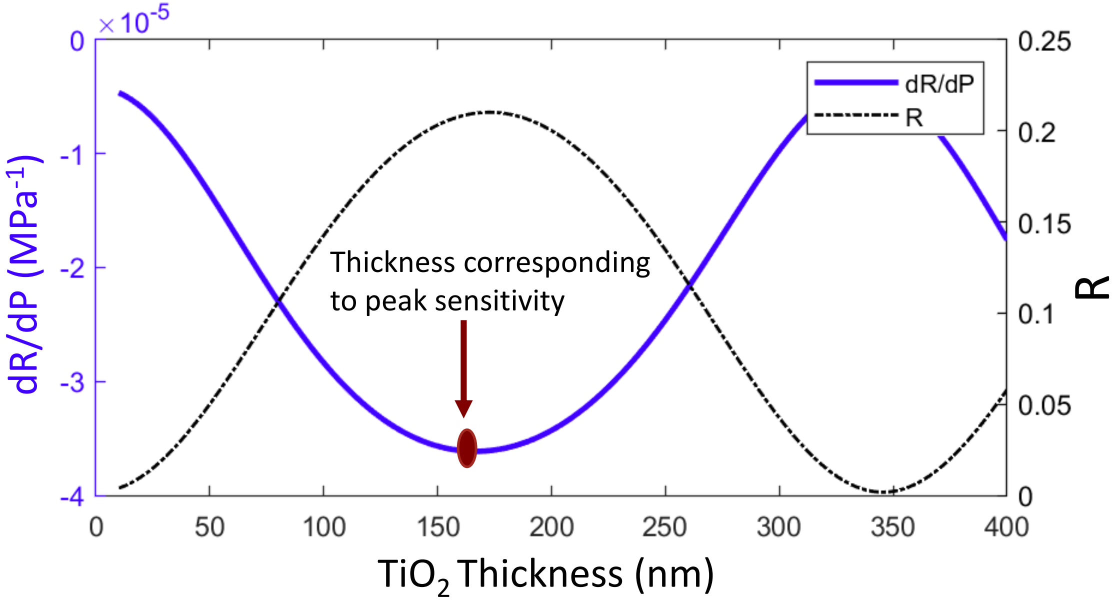
3) The variation of refractive index of the fluid with pressure change

$$\frac{\Delta n_w}{\Delta P} = 1.36\text{x}10^{-4}\ /\text{MPa}$$

Wilkens, V., and Ch. Koch, 1999

RESULTS (MODEL)- SINGLE LAYER COATED FOH

R, dR/dP versus TiO_2 Thickness at 1565 nm

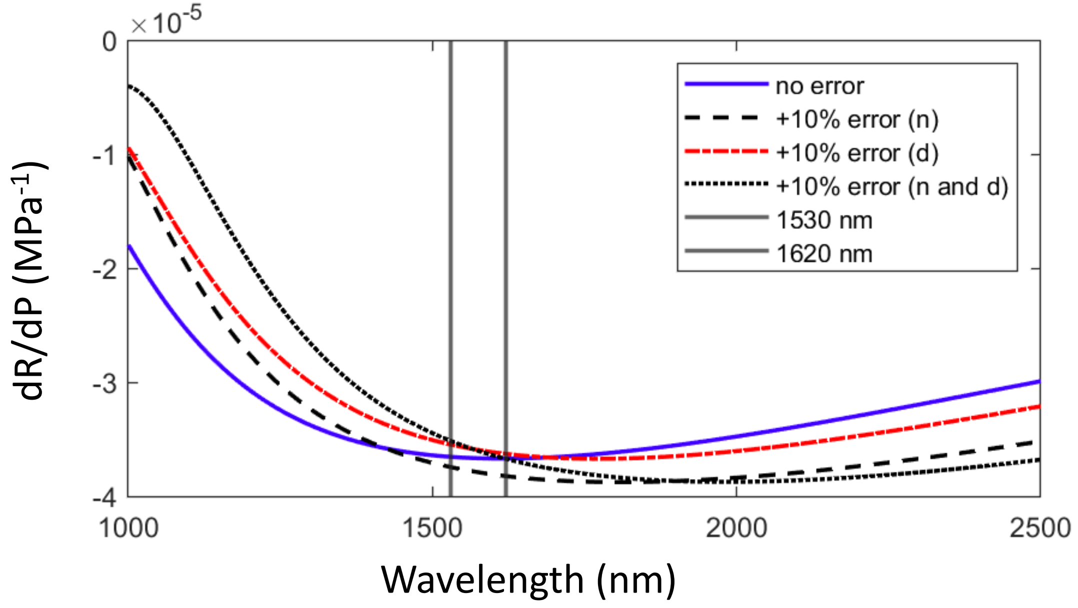


TiO_2 coated (172 nm) $\left|\frac{dR}{dP}\right|$=3.61x$10^{-5}$ /MPa

Uncoated $\left|\frac{dR}{dP}\right|$=4.23x$10^{-6}$ /MPa

Sensitivity increase=8.5 (relative to an uncoated FOH)

dR/dP versus Wavelength (172 nm TiO_2 coating)

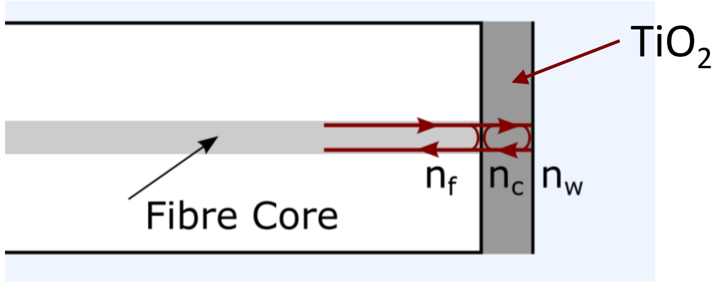


One layer configuration allows for >10% error

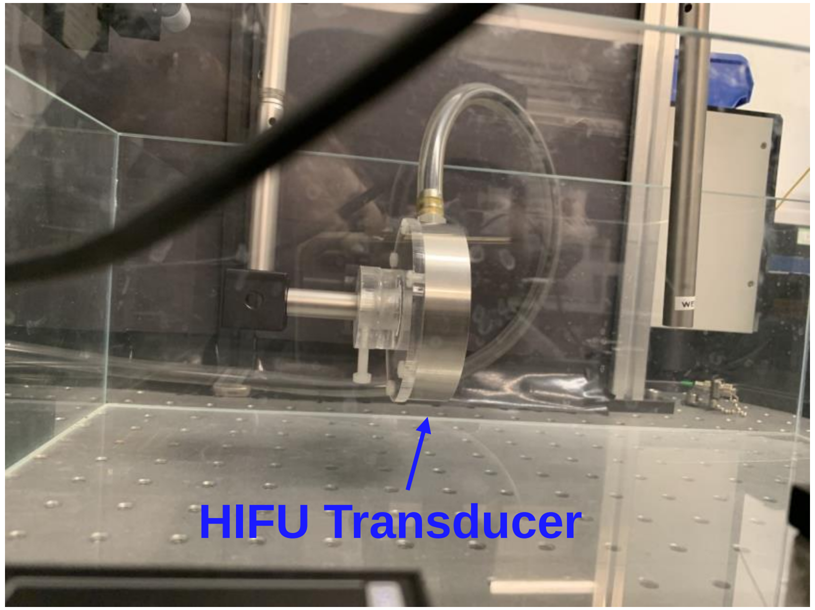
METHODS- EXPERIMENTAL SETUP

Fabrication of Sensors

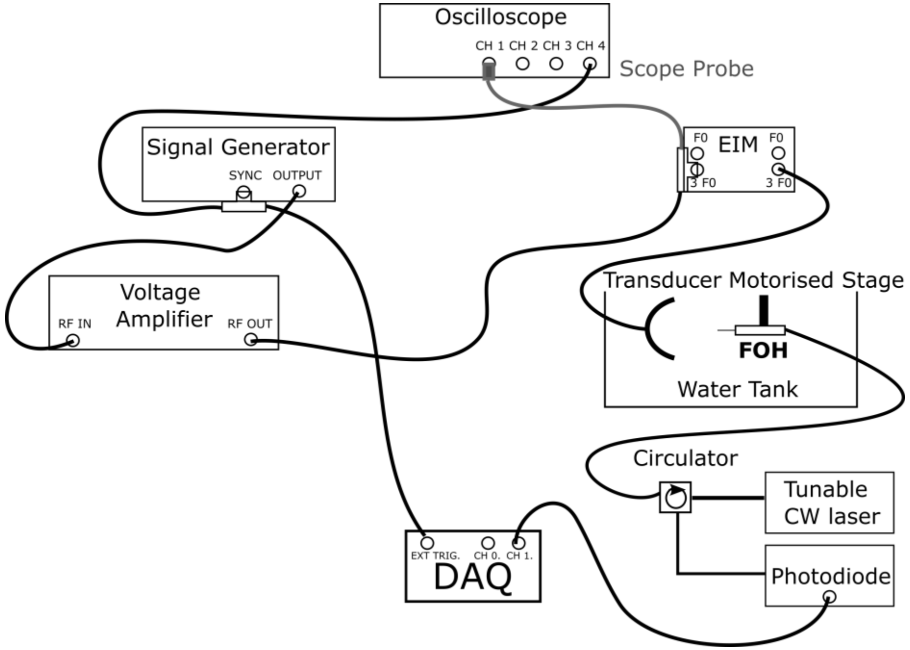
Single-layer coated FOHs were fabricated via plasma-assisted e-beam deposition of a quarter-wave layer (172 nm) of TiO_2.



Experimental Set-up

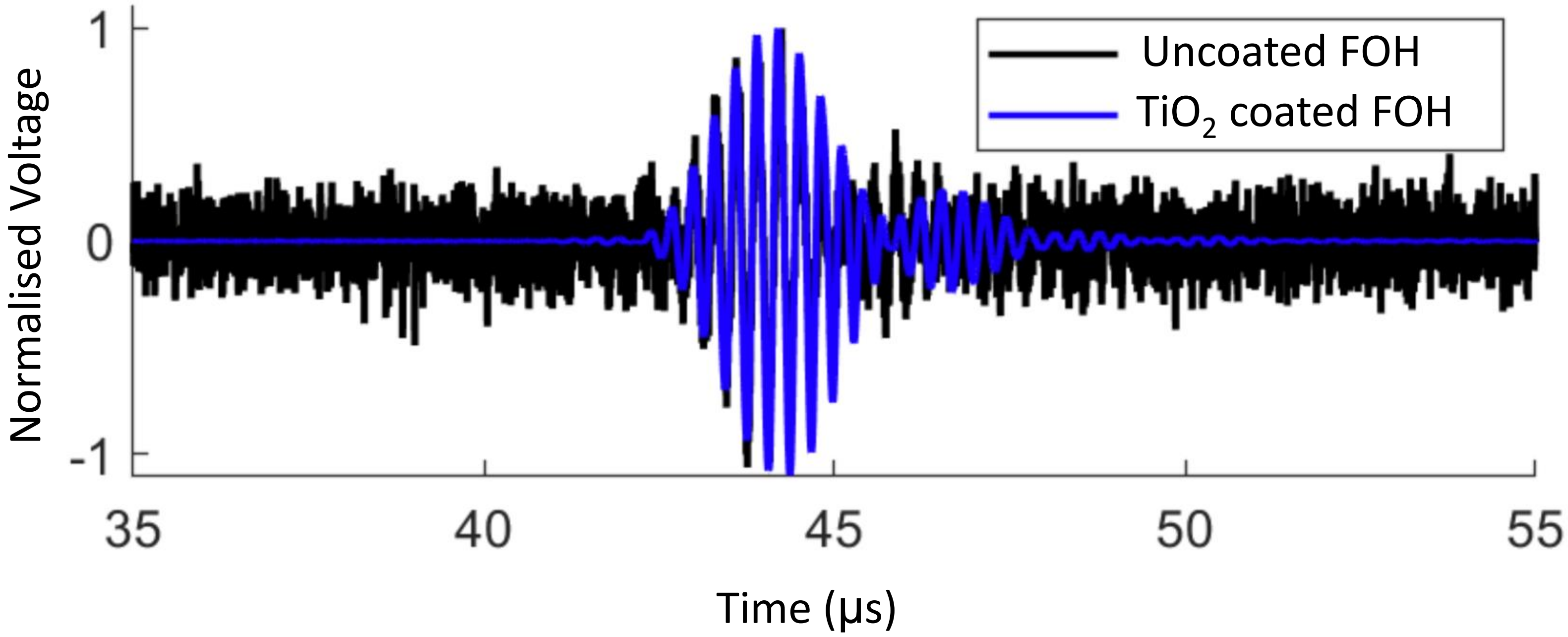


Diameter: 64 mm, focal length: 62.3 mm
Fundamental frequency= 3.3 MHz



Schematic of the experimental setup

RESULTS (EXPERIMENTS)- SINGLE LAYER COATED and UNCOATED FOHs

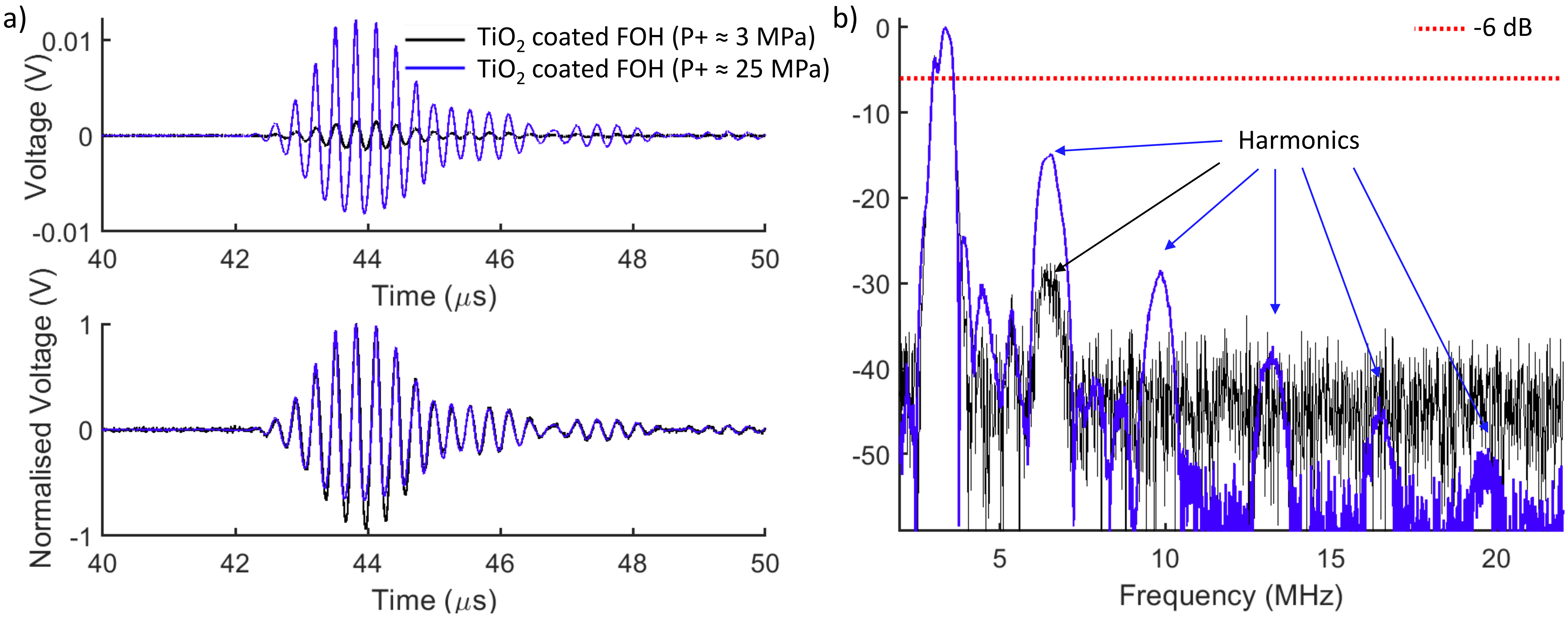


Measured pressure time series at the focus of a HIFU transducer (1000 averaging, 3.3 MHz, 4-cycle bursts, peak-positive pressure ≈ 3 MPa) with the uncoated and single-layer TiO$_2$ coated FOHs.

SNR of TiO$_2$ coated=23 dB
SNR of uncoated=1.9 dB

The coated sensor endured prolonged pressures **over 35 MPa peak positive and 22 MPa peak negative**.

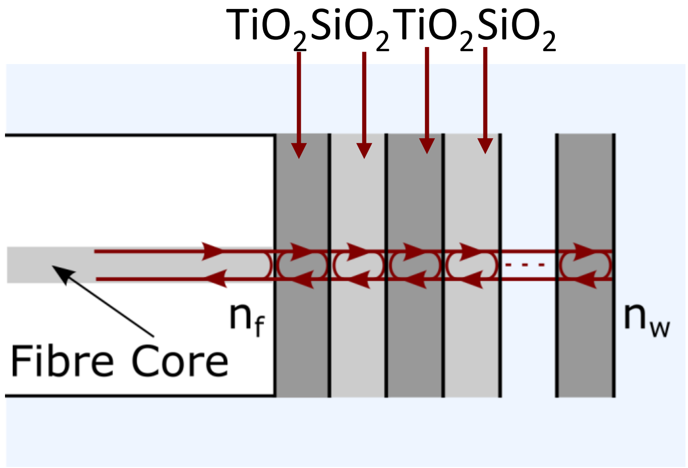
RESULTS (EXPERIMENTS)- SINGLE LAYER COATED FOH



a) Measured waveforms and b) frequency spectra at the focus of the HIFU transducer with the single-layer TiO$_2$ coated FOH.

METHODS - SIMULATION MODEL

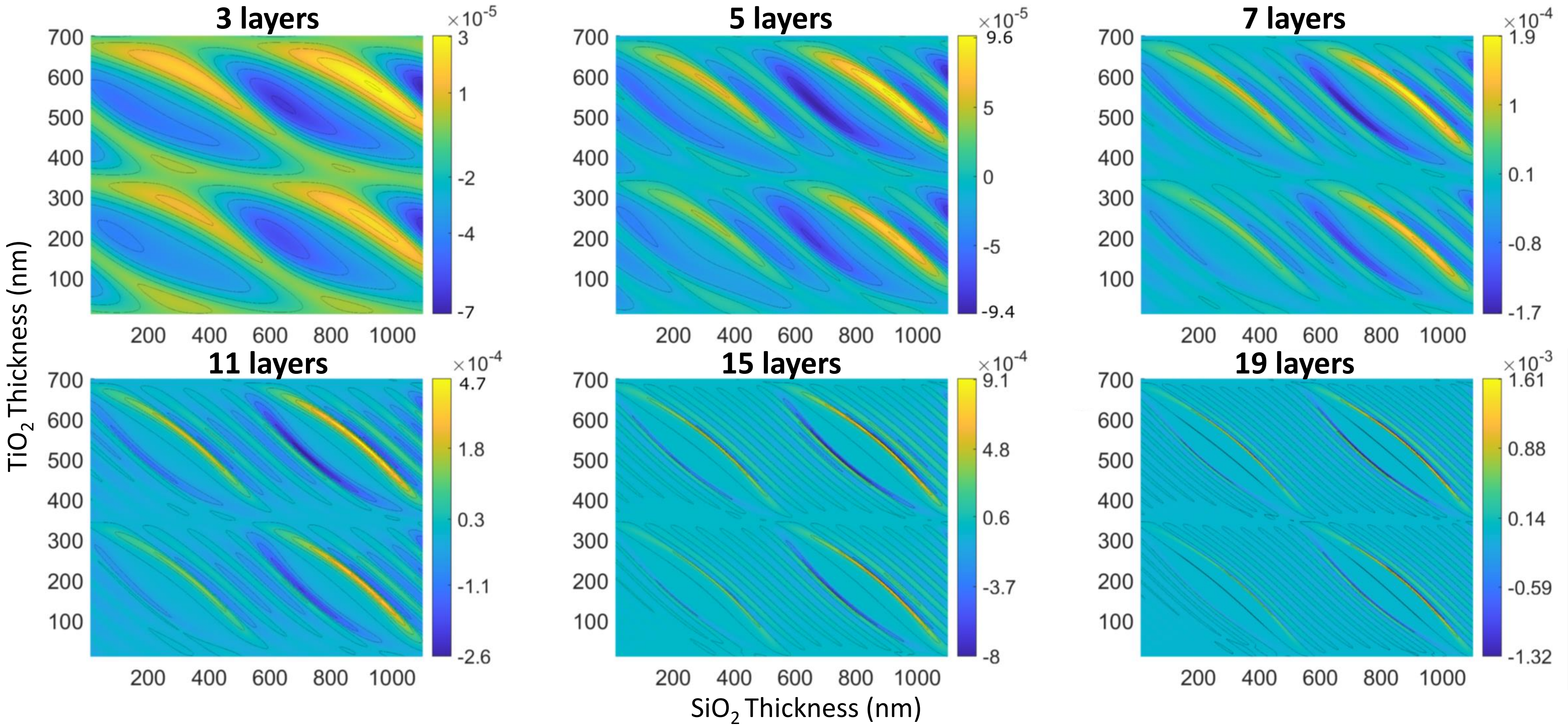
Simulations are performed for multiple alternating layers of TiO_2 and SiO_2-coated FOHs.



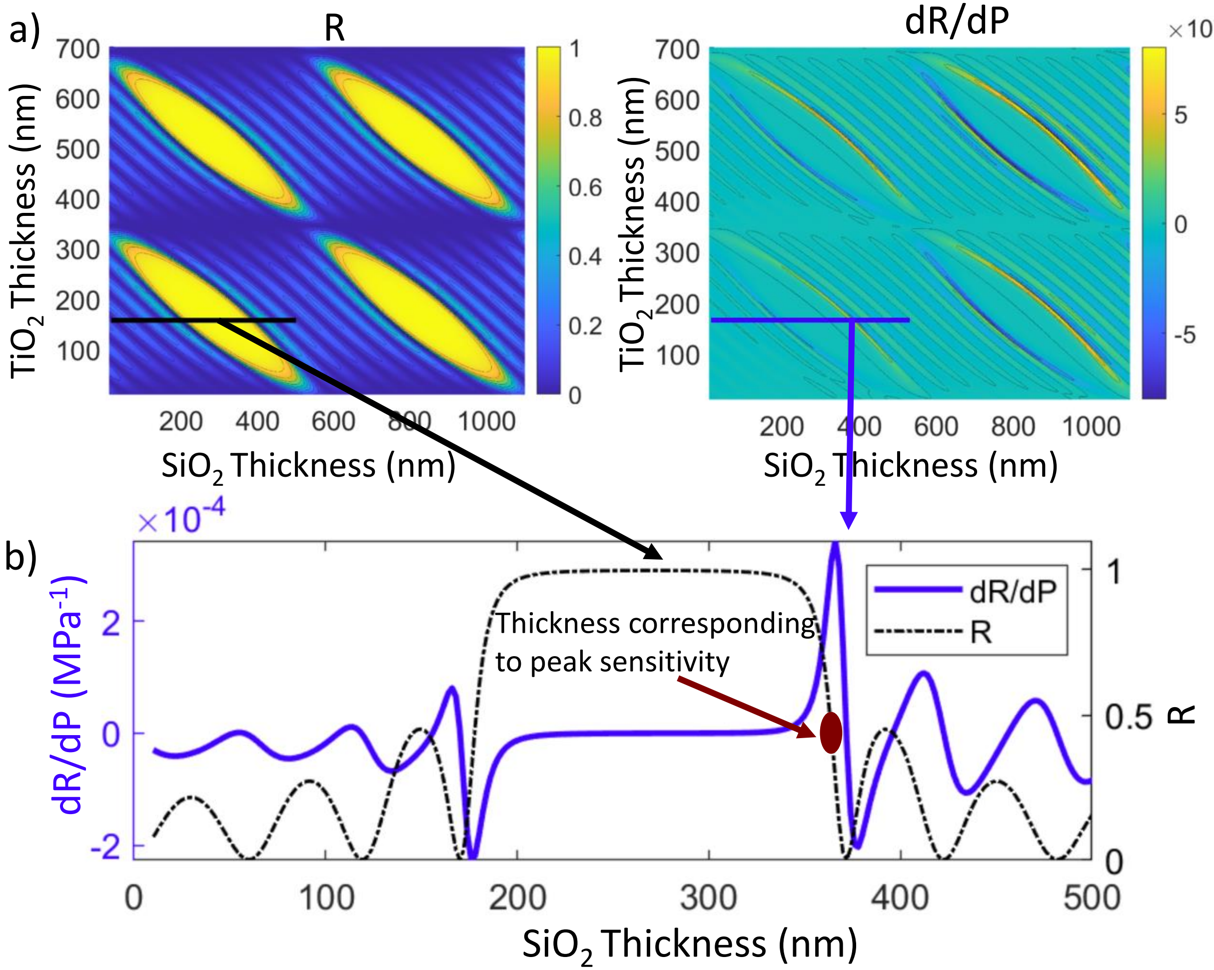
Schematic of a coated FOH.

For total layer numbers up to 5, as a response to pressure changes, the reflectivity modification at the sensor-fluid interface was found as the main contributor to the sensitivity of FOHs. For total layer numbers over 5, the optical path length change dominates.

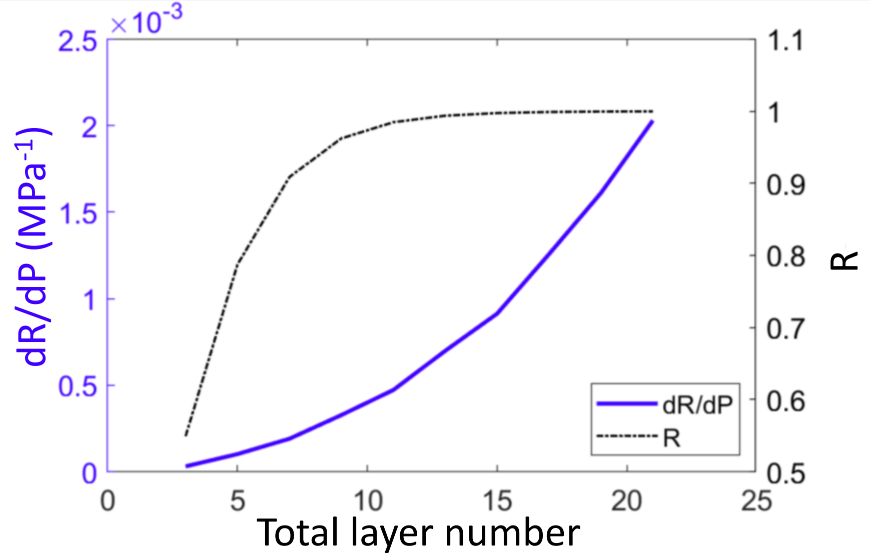
RESULTS (MODEL)- dR/dP CONTOUR MAPS of MULTI-LAYER COATED FOHS



RESULTS (MODEL)- MULTI-LAYER COATED FOHs



a) Contour plots of R and dR/dP for a 15-layer coated FOH, b) R and dR/dP plots when the thickness of TiO_2 layers are 172 nm.



Total layer #	|dR/dP| (maximum)	Sensitivity increase compared to an uncoated FOH
1	3.61×10^{-5} MPa^{-1}	8.5
3	4.19×10^{-5} MPa^{-1}	9.9
9	1.20×10^{-4} MPa^{-1}	28
15	3.43×10^{-4} MPa^{-1}	81

$|dR/dP|_{max}$ values for various FOH configurations. $|dR/dP|_{max}$ value of an **uncoated FOH** was calculated as 4.23×10^{-6} MPa^{-1}.

CONCLUSIONS

- A simulation framework that models coated fibre-optic hydrophones was developed. (e.g. reflectance, derivative of reflectance with respect to the pressure (as a function of coating thickness and wavelength))
- Single-layer coated FOHs were fabricated via plasma-assisted e-beam deposition of a quarter-wave layer (172 nm) of TiO_2.
- Sensitivity gain of 11.0x was observed experimentally with a single-layer TiO_2 coated FOH (172 nm).
- This coated hydrophone endured prolonged pressures over 35 MPa peak positive and 22 MPa peak negative.
- Simulations show that the sensitivity could be significantly improved further. For instance, a 15-layer structure of alternating TiO_2 and SiO_2 coatings was predicted to achieve an increase in sensitivity of ca. 81 while still being mechanically robust for HIFU applications.

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REFERENCES AND ACKNOWLEDGEMENTs

References

1) Wurster, C., Staudenraus, J., & Eisenmenger, W. (1994, October). The fiber optic probe hydrophone. In *1994 Proceedings of IEEE Ultrasonics Symposium* (Vol. 2, pp. 941-944). IEEE.
2) Smith, N., Sankin, G. N., Simmons, W. N., Nanke, R., Fehre, J., & Zhong, P. (2012). A comparison of light spot hydrophone and fiber optic probe hydrophone for lithotripter field characterization. Review of Scientific Instruments, 83(1), 014301.
3) Wilkens, V., & Koch, C. (1999). Fiber-optic multilayer hydrophone for ultrasonic measurement. Ultrasonics, 37(1), 45-49.
4) Katsidis, C. C., & Siapkas, D. I. (2002). General transfer-matrix method for optical multilayer systems with coherent, partially coherent, and incoherent interference. Applied optics, 41(19), 3978-3987.

Acknowledgements

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