Supplementary Information

Holographic Direct Sound Printing

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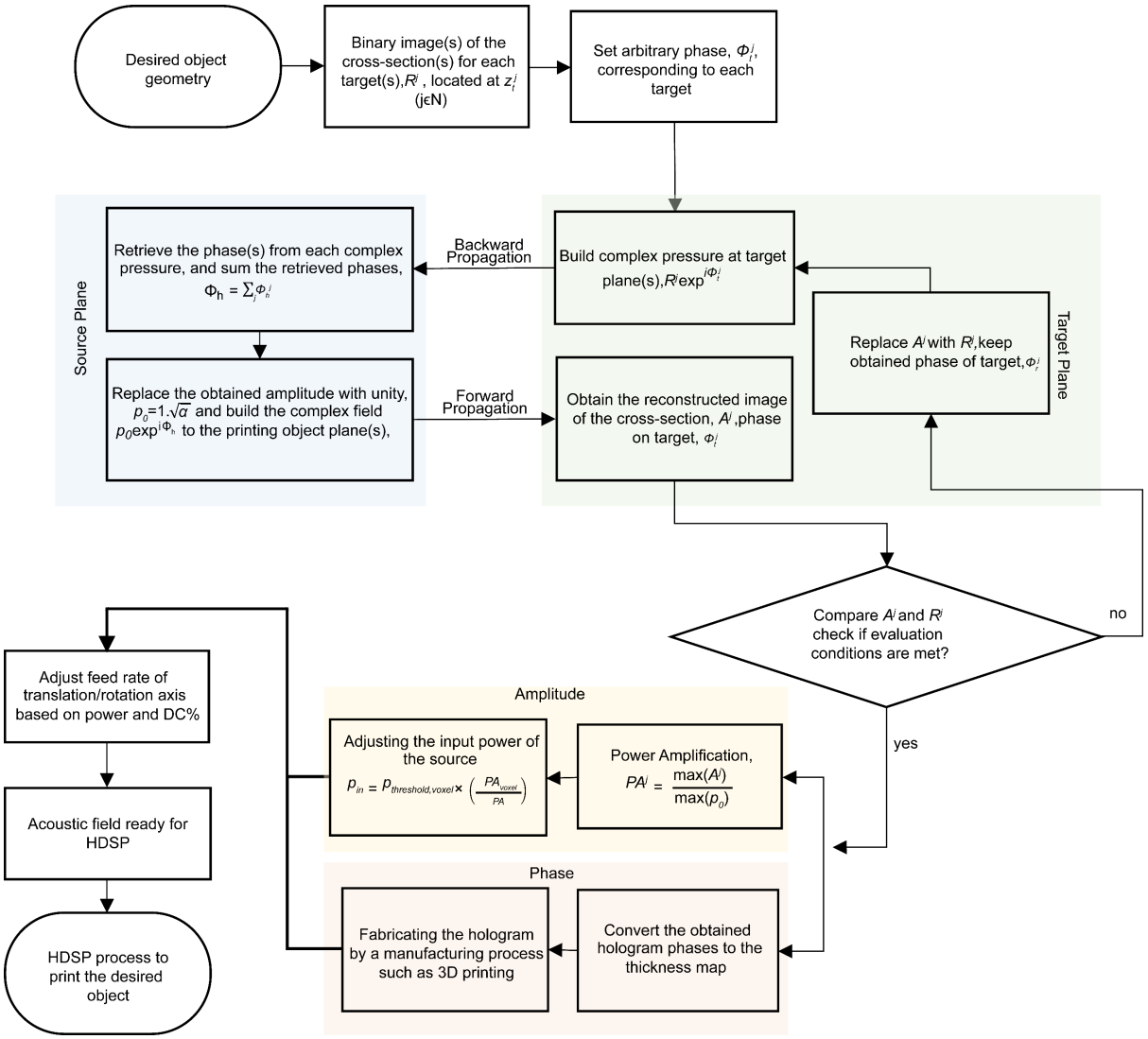
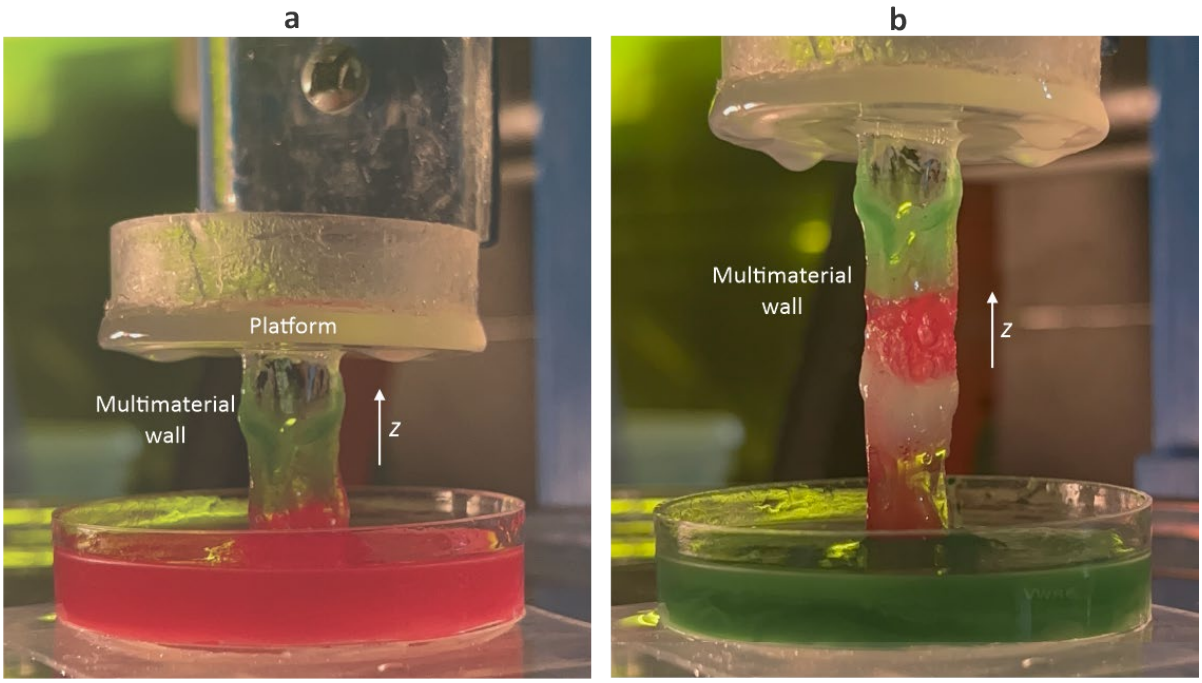
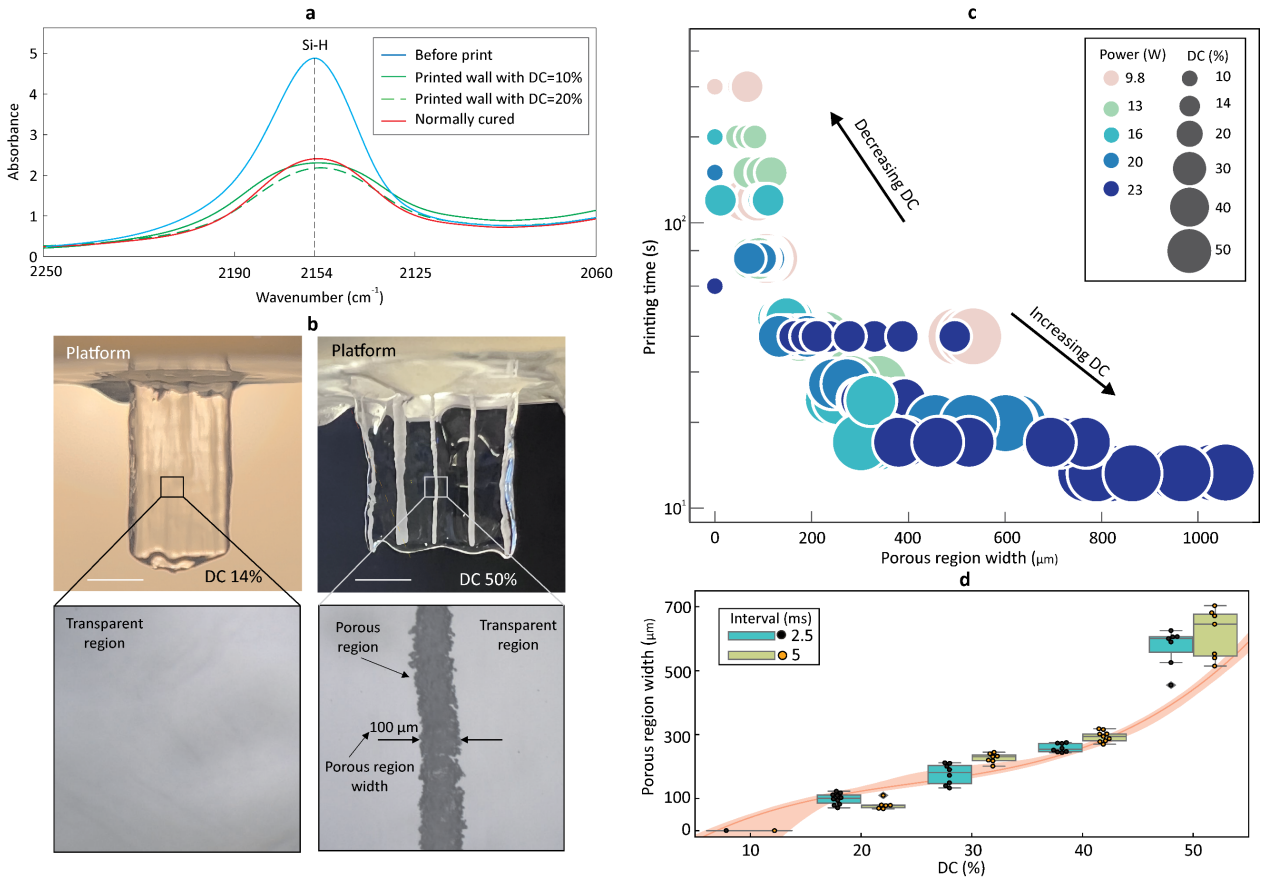


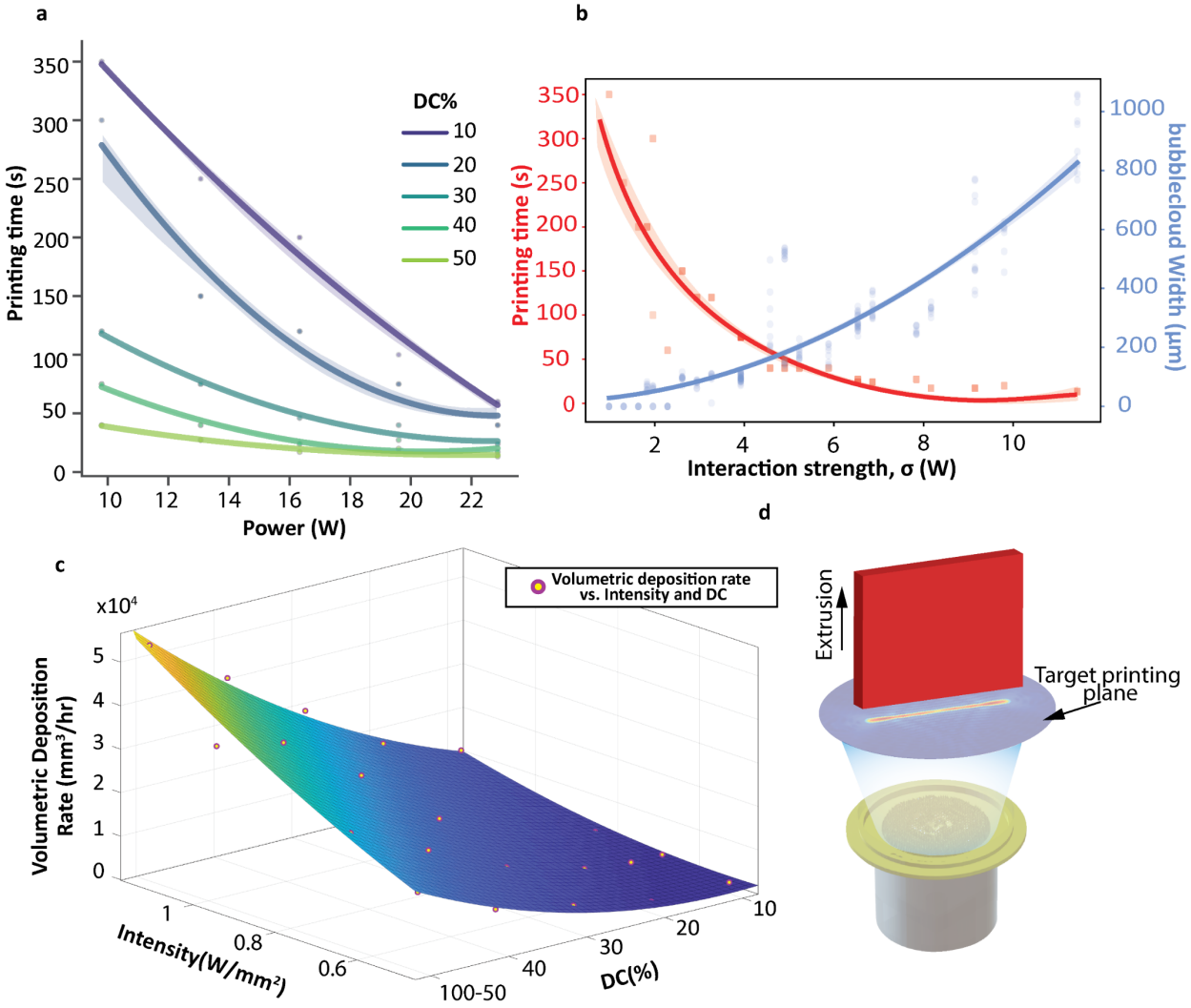
Supplementary Fig. 1. HDSP process flow, starting from creating acoustic holography field required for HDSP.



Supplementary Fig. 2. (a) and **(b)** Sequential multi-material printing in HDSP, transparent PDMS followed by green, red and white dyed PDMS are printed. Printing parameters: OD = 25 mm, P = 8 W, f_0 = 2.24 MHz, DC = 50%.

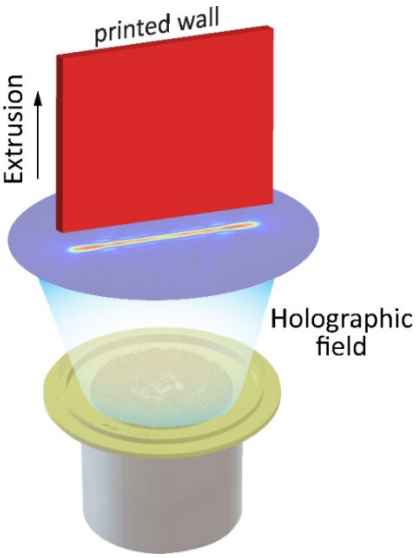
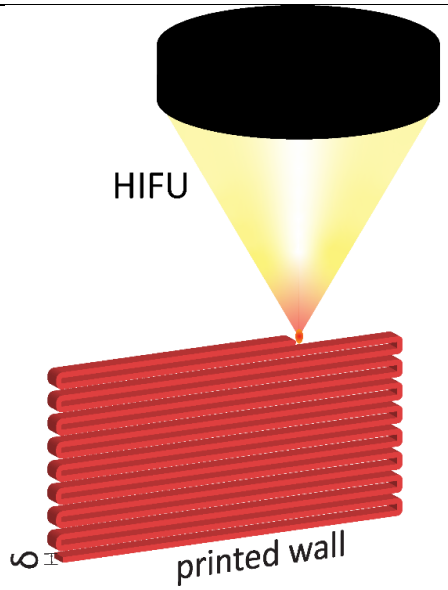
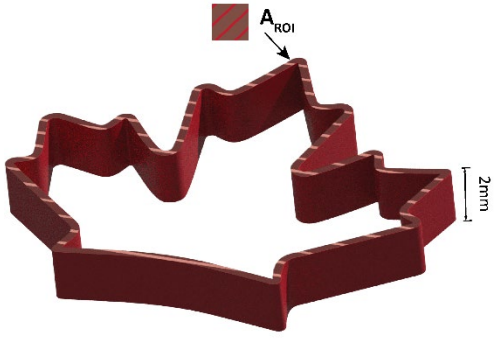
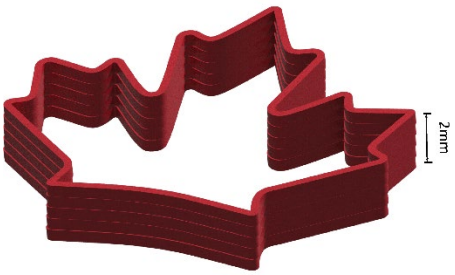


Supplementary Fig 3. Material and microstructure characterization of the printing process. **(a)** comparison of IR spectrum for Si-H (2154 cm^{-1}) for printed line with 10%, 20%, normally cured PDMS and that of uncured PDMS. **(b)** Displays the printed parts with DC settings at 50% showing bubble cloud formation and at 14% without bubble clouds, respectively. Scale bars represent 10 mm. The extended view showing the 10x magnified view of the bubble cloud. **(c)** A comprehensive experimentally-obtained graph illustrating the relation between printing parameter such as, power and DC% on width of micro-bubble cloud formed within the part and printing time for a HDSP wall object extruded 10mm in z-direction. Changing the interval as another printing parameter and impact the bubble cloud formation, which shown in **(d)** with burst signal intervals of 2.5 ms and 5 ms indicated by black and yellow dots, respectively, for various *DC*%. The box plots showing quartiles and range, and a fitted curve with a confidence band.



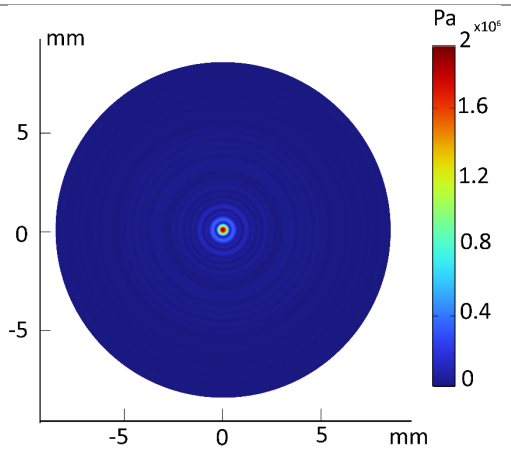
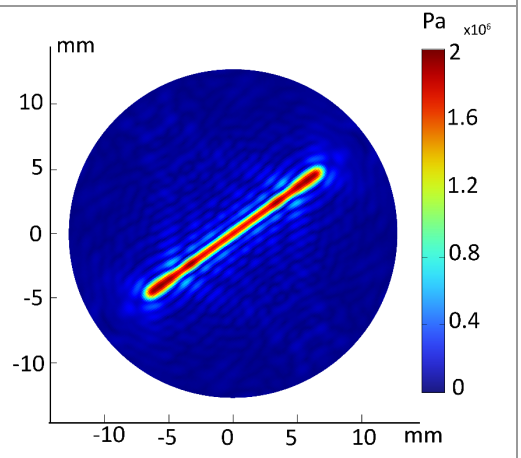
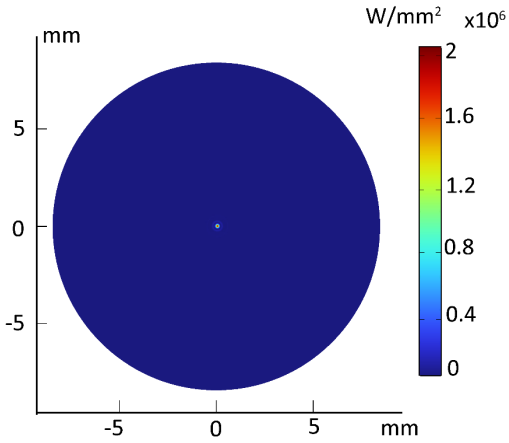
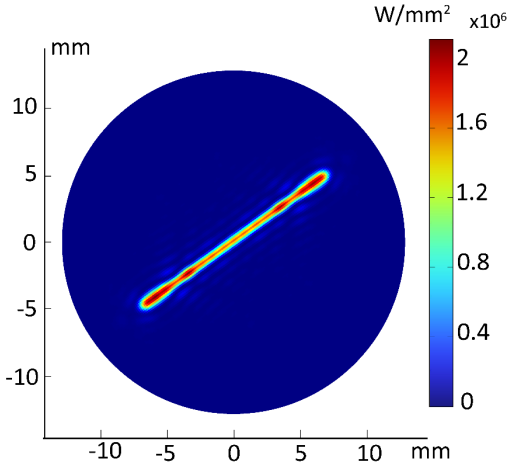
Supplementary Fig. 4. (a) The relationship between power and printing time for the wall printing, with the printing process schematic shown in (d). **(b)** Relationship between the effective power parameter, Interaction strength σ(W), and Printing time (s) (shown in red), alongside bubble cloud formation width (μm) (shown in blue). **(c)** Volumetric Deposition Rate (mm^3/hr) interpolated with respect to the intensity (W/mm^2) and DC(%). **(d)** Schematics of the HDSP performing wall printing using a line geometry as the target object.

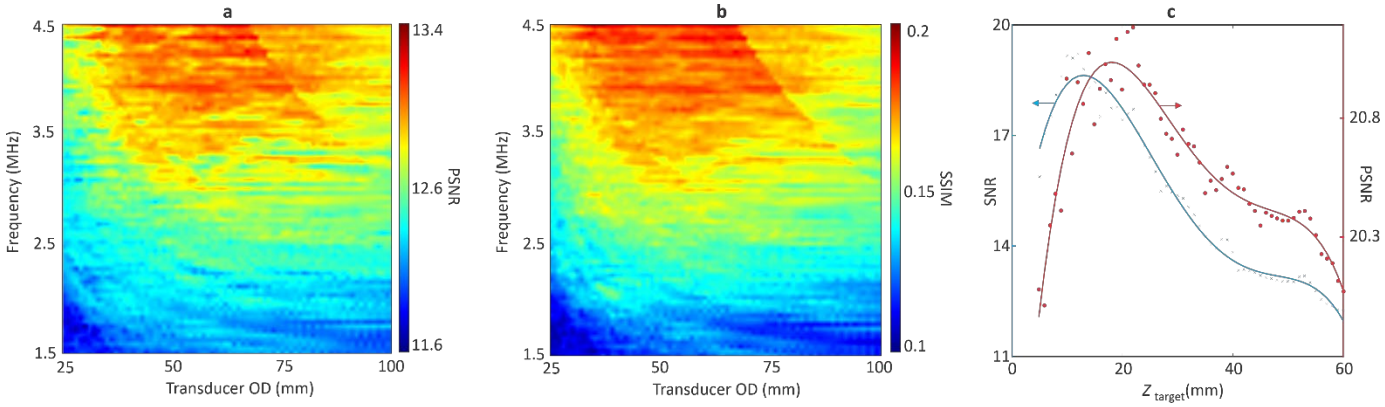
Supplementary Table 1. Printing time predication for HDSP vs DSP.

Printing mechanism	HDSP	DSP
Schematics of printing **Case study: Wall**		
Time formulation	$time_{HDSP} = \frac{Volume}{VDR(I, DC(\%))}$ The calculation of Intensity and VDR function is presented in Eq. S1	$time_{DSP} = \frac{length\ of\ path}{feed\ rate}$
Time of print for Wall of 15×1×20mm^3 (from actual Experiment)	$time_{HDSP}$: 0.25 − 5min Printing transparent wall with moderate power setting: $time_{HDSP} = \mathbf{1.86\ min}$	• Length of path/layer (mm) = 15 • Wall height=20mm • Layer thickness≈0.3mm • Number of layers (transversal)=20mm/0.3mm=67 • Number of layers (lateral)=1mm/0.3mm≈3 • Total length = 15×3×67(mm) • Feed rate (mm/min) = 240 $time_{DSP} = \frac{Total\ length}{Feed\ rate} = \mathbf{12.56min}$
Example Geometry: Maple		
Example of theoretical prediction of the time to	$T_{\mathrm{HDSP}} = \frac{(\mathrm{A_{ROI}} \times 2\mathrm{mm}^3)}{\mathrm{VDR}\left(\frac{45W}{\mathrm{A_{ROI}}}, 50\%\right)}$ $= \mathbf{14.35s}$	• length of path/layer (mm) = 61.0 • Part thickness=2mm • Each layer thickness≈0.3mm • Number of layers=7 • Total path length = 61.0×7(mm)

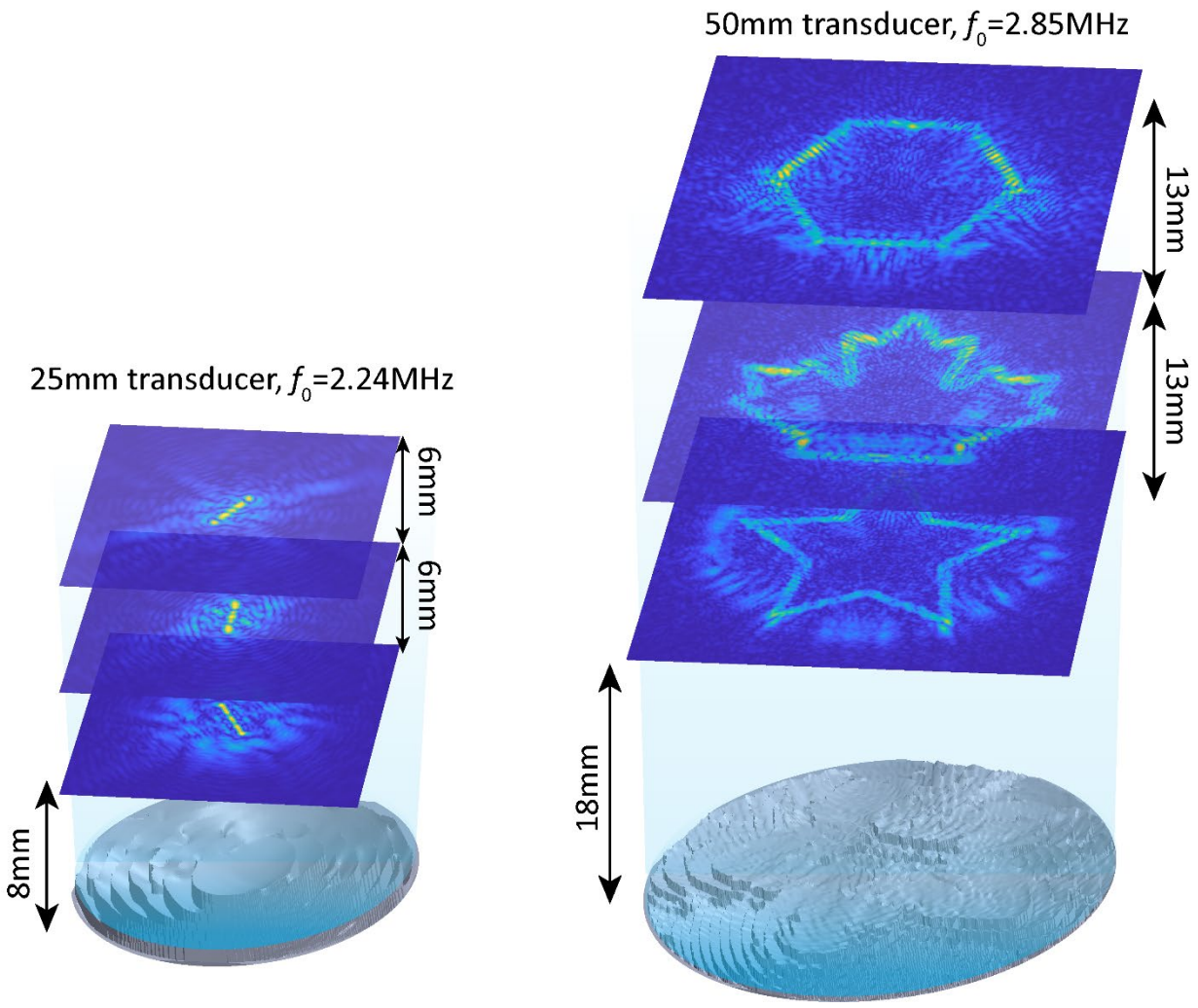
print: Maple leaf object with 2mm thickness		• Feed rate (mm/min) = 240 $T_{\mathrm{DSP}} = \frac{Total\ length}{Feed\ rate} = \mathbf{1.77min}$

Supplementary Table 2. Comparison of the HDSP vs DSP in terms of deposition power, total deposition energy and energy density

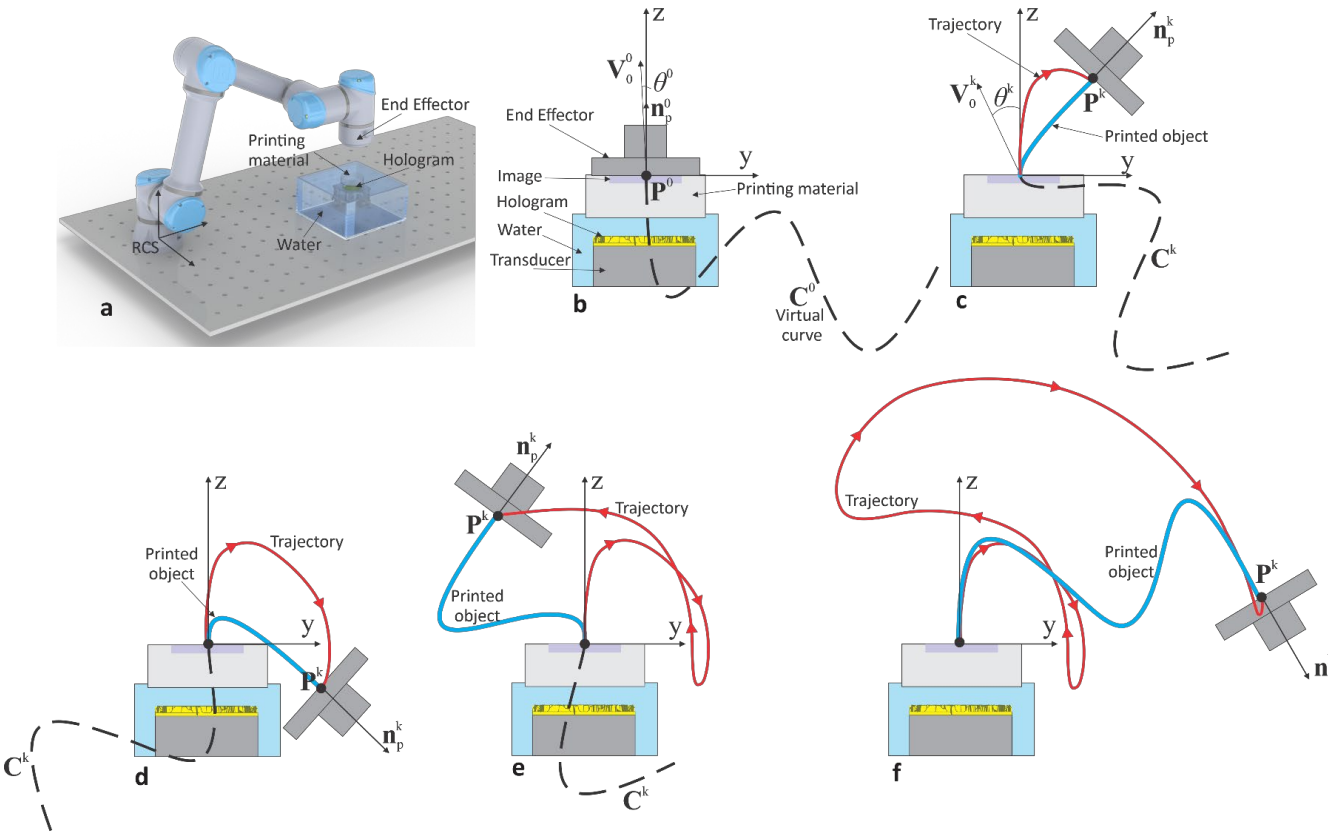
Printing mechanism	**DSP**	**HDSP**
Frequency (MHz)	2.15	2.24
Geometry and area of the target image	Focal point, 0.3848 (mm^2)	Line, 6.63 (mm^2)
Pressure pattern		
Intensity pattern(W/mm^2)		
Deposition power at the image plane (W)	1.18	23.18
Total Printing Time (min)	~12.56	~0.5
Total Energy Deposition (J): power × time	**Simulation:** 1.18W×12.56×60=889.25	**Simulation:** 23.18W×0.5×60=695.4
Total Energy Input to the system (J)-(from experiment)	**Experiment:** 10W×12.56×60=7536J	**Experiment:** 30W×0.5×60=2790



Supplementary Fig. 5. (a) PSNR and **(b)** normalized SSIM surface plots for reconstructed image quality measure by varying frequency, f_0 and source aperture, *OD*. **(c)** SNR curve (blue colored) and PSNR curve (red colored) showing the dependency of the generated image to the various target plane in z-direction, for transducer with {*OD*=25mm, f_0=2.24 MHz} and {*OD*=50mm, f_0=2.28 MHz}, respectively.



Supplementary Fig. 6. Reconstruction for Multi-plane object printing capability with HDSP. Input parameter of transducer OD25mm and 2.24MHz frequency with 191×191 element hologram generating various line images (Left) and transducer OD50mm and 2.85MHz frequency with 386×386 element hologram (Right)



Supplementary Fig. 7. (a) Robot-assisted HDSP. **(b)-(f)** Subsequent steps of printing an object with the computed trajectory.