Supplementary Information for

Metamaterial-Based Passive Analog Processor for Wireless Vibration Sensing

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Besides the main manuscript and supplementary, we also submitted five videos to support our work. The information of them is listed here:

Video S1. The video for vibrating object segmentation and moving trajectory extraction of the device with the eigenfrequency of 110 Hz. The input vibration has a frequency of 110 Hz.

Video S2. The bottom layer movement (input vibration) of the device with the eigenfrequency of 285 Hz and input frequency of 285 Hz.

Video S3. The top sphere movement (output vibration) of the device with the eigenfrequency of 285 Hz and input frequency of 285 Hz.

Video S4. The fluorescent layer movement of the device with the eigenfrequency of 125 Hz and input frequency of 125 Hz in a bright environment.

Video S5. The fluorescent layer movement of the device with the eigenfrequency of 125 Hz and input frequency of 125 Hz in a dark environment.

Supplementary Notes

Simulation of the devices

We simulated the vibration properties of the devices using COMSOL Multiphysics 6.0 structural mechanics module. The 2D axisymmetric simulation is used. The Young's modulus of membrane is set as 3.89×10^{10} pa. The mass density of membrane is set as 1390 kg/m^3 and Poisson's ratio is 0.48. The other parameters used in simulations are listed in supplementary Table S1. Those parameters are swept to observe their influence on the device's eigenfrequencies. The results are shown in Supplementary Fig. S2.

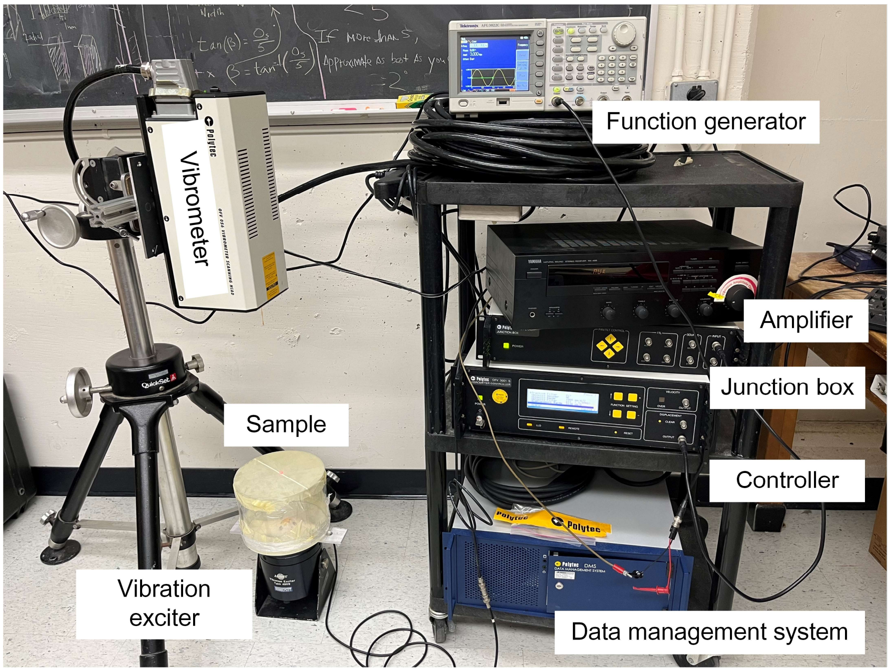

Fig. S1. Experiment setup of vibration measurement using laser vibrometer.

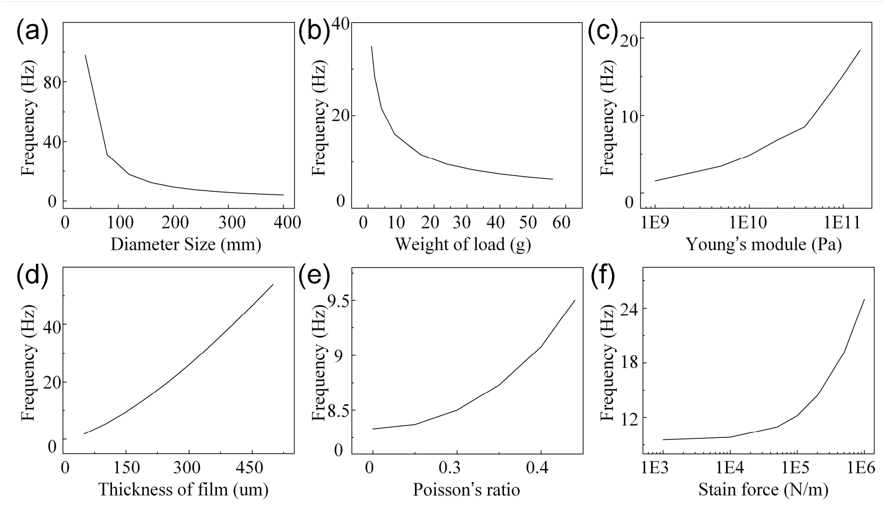

Fig. S2. The influence of parameters in device. The first eigenfrequency of the device with the sweep of (a) membrane diameter, (b) weight of the loaded mass, (c) Young's modulus of the membrane, (d) thickness of the membrane, (e) Poisson's ratio of the membrane, and (f) static stain in the membrane. In each plot, only one parameter is swept. The initial values of all the parameters are: membrane diameter of 200 mm, loaded mass weight of 32 g, membrane Young's modulus of 38.9 GPa, membrane thickness of 150 μm, membrane Poisson's ratio of 0.48, strain stain in the membrane of 0 N.

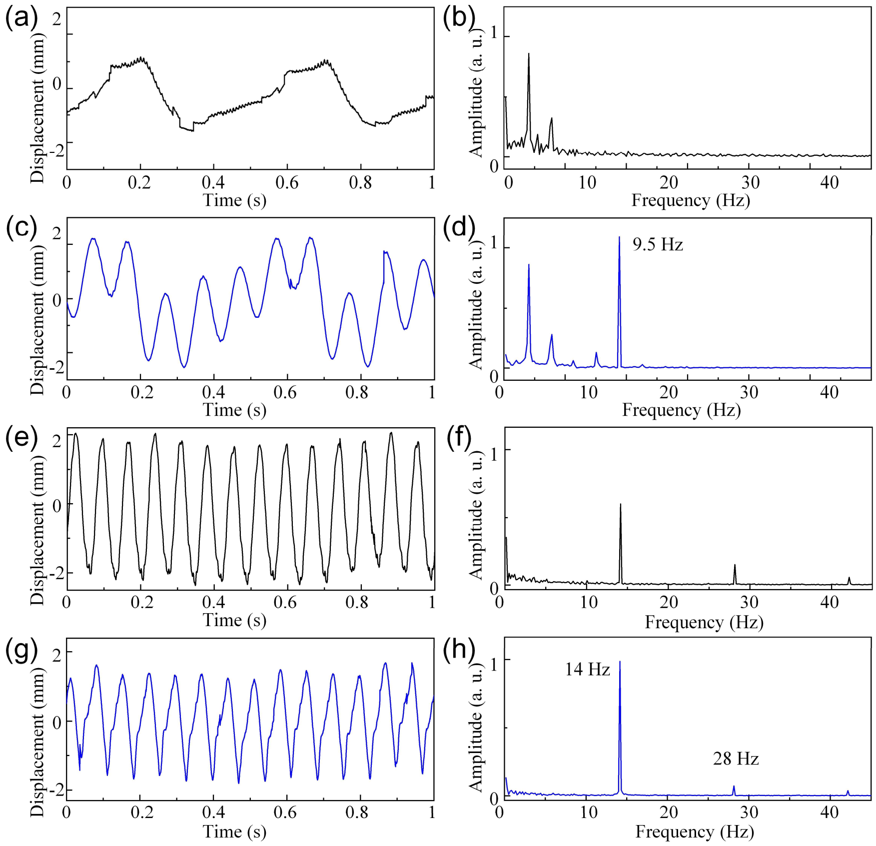

Fig. S3. Experimentally measured output vibrations of the device and their frequency spectra when the input vibration frequency is not eigenfrequency. (a-d) The input vibration (a) and output vibration (c) with a quasi 2 Hz triangle wave input. (b) and (d) are the frequency spectra of (a) and (c), respectively. (e) and (g) The input vibration (e) and output vibration (g) with a 14 Hz quasi sinusoidal wave input. (f) and (h) are the frequency spectra of (e) and (g), respectively.

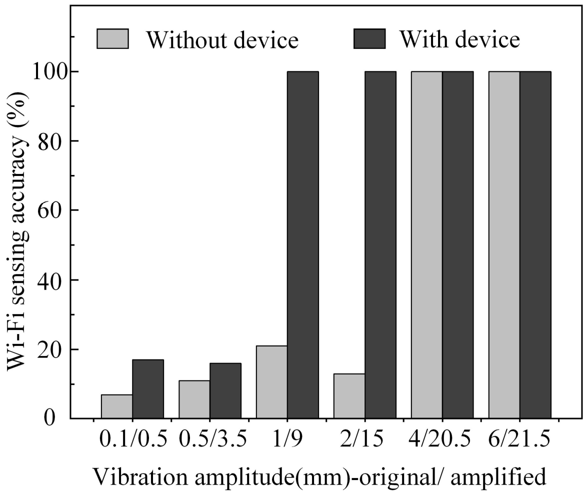

Fig. S4. The accuracy of the Wi-Fi based vibration detection with or without the device.

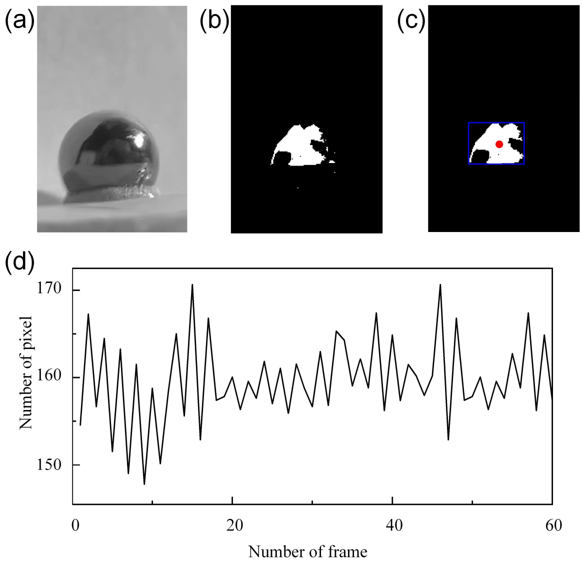

Fig. S5. Demonstration of the vibration extraction from a video using the object segmentation method. (a) A grayscale snapshot of the recorded video. (b) The black-and-white picture of (a) based on a grayscale threshold. (c) The centroid of (b) is shown as the red point. (d) The movement of the centroid as a function of time in the video, showing the vibration of the loaded mass.

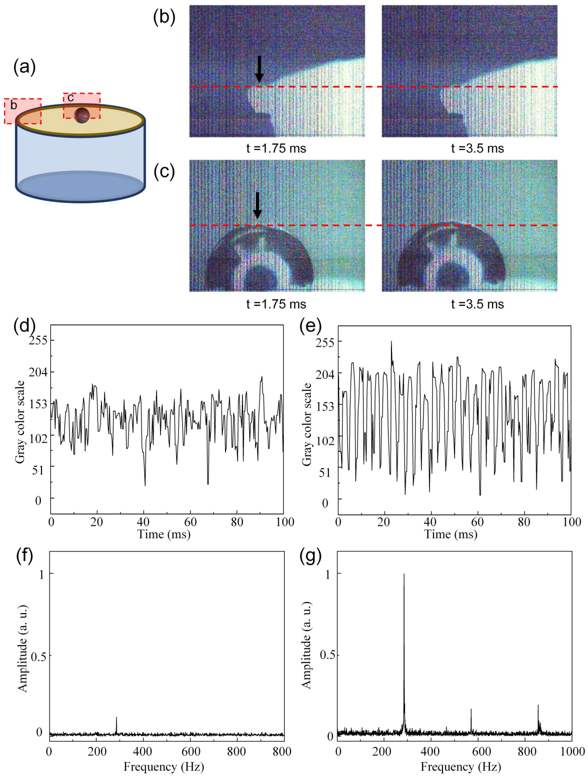

Fig. S6. Demonstration of the vibration frequency extraction from a recorded video for the device with an eigenfrequency of 285 Hz based on the sample boundary analysis method. (a) Demonstration of the recorded areas in videos S2 (the area marked with letter b) and S3 (the area marked with letter c) for the monitoring of the outer shell and center sphere of the device. (b) The snapshots at t = 1.75 ms and t = 3.5 ms of the recorded shell movement (input vibration) from supplementary video S2. The movement of the outer shell is tiny and difficult to distinguish. (c) The snapshots at t = 1.75 ms and t = 3.5 ms of the recorded movement of the top sphere (input vibration) from supplementary video S3. (d) and (e) The grayscale value as a function of time of one point (marked with arrows in (b) and (c)) at the boundary of the outer shell (d) and the top sphere (e). (f) and (g) are the frequency spectra of (f) and (g), respectively.

Supplementary Table S1. The design parameters of the devices

Device number	**1**	**2**	**3**	**4**	**5**
Eigenfrequency	9.5 Hz	110 Hz	285 Hz	125 Hz	5 Hz
Weigth of loaded mass (g)	32	1.7	0.3	2	45
Diameter (mm)	200	20	10	20	200
Material & thickness of the film	Silicone rubber, 0.15 mm				
Membrane editing	-	-	-	fluorescent layer Coating	Loaded with a reflector
Sensing system	Wi-Fi sensing	Camera sensing	Camera sensing	Camera sensing	Wi-Fi sensing

Supplementary Algorithm Table S2. Wi-Fi sensing algorithm

Algorithm 1: WiFi sensing algorithm

Data: $CSI_{stream\text{-}1}$, $CSI_{stream\text{-}2}$, $|f_{low}, f_{high}|$

Result: $f_{1\text{-}max}, \ldots, f_{i\text{-}max}, \ldots, f_{n\text{-}max}$

start-ix = 0;

window-size = w;

finish-ix=start-ix + window-size;

phase-difference = CSI-Ratio (angle ($CSI_{stream\text{-}1}$), angle ($CSI_{stream\text{-}2}$));

While *size(phase-difference) = finish-ix* **do**

  PSD = plomb (phase – difference (start-ix, finish-ix));

  $f_{i\text{-}max}$=arg $\max_x$(PSD);

  start-ix = finish-ix;

  finish-ix = start-ix + window-size;

end
