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Slow sound based delay-line acoustic metamaterial

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Abstract

Periodic structures composed of quarter-wavelength or Helmholtz resonators have been widely used in the design of acoustic metamaterials. An interesting phenomenon achievable through hybridization in such structures is the slow sound, which results from the strong dispersion produced by the local resonances. It gives rise to many applications such as deep sub-wavelength sound absorbers or metadiffusers. All the applications proposed so far have been analyzed only in the frequency domain (steady state). In this work, we propose a passive treatment that can be used in room acoustics, which requires considering the time domain and all multiple reflections. We analytically design a delay line from a metasurface made of Helmholtz resonators, using slow sound propagation. We prove numerically and experimentally that such structures can delay a pulse and thus reproduce the sound perception of a propagation over a given distance, larger than the actual size of the treatment. The limitations of real-time pulse propagation, dispersion, and losses on audio fidelity are discussed.

19 The control of acoustic waves for room acoustics applications has been of constant interest
20 for centuries, for two main purposes: to control diffusion and to enhance absorption. From the
21 first Helmholtz resonators used in antique amphitheaters and the Schroeder's diffusers principle
22 [1], a long road has been traveled to more sophisticated systems such as active electroacoustic
23 devices [2, 3], virtual sources and immersive boundaries [4–7], optimized graded porous materials
24 [8], or acoustic metasurfaces and metamaterials [9–14]. The great advantage of the latter is that
25 they offer the possibility of tackling the device thickness/frequency paradigm. A thickness greater
26 than the quarter of the acoustic wavelength is usually required to attain a good efficiency for
27 both phenomena, absorption or diffusion. In particular, Yang *et al.* defined a causality-dictated
28 inequality stating the optimal absorption spectrum as a function of sample thickness [15], which
29 inevitably leads to a compromise between working frequency bandwidth and thickness. It is worth
30 noting here, that recently, Mak *et al.* proposed a new design based on soft boundaries to go beyond
31 this causal limit [16].

32 The search for deep sub-wavelength sound absorption has been one of the main avenues for
33 the development of acoustic metamaterials and metasurfaces [10, 17, 18]. Several strategies have
34 been employed to address this challenge, both in transmission [11, 18–21] and reflection [22–
35 24] problems: soft boundaries [16], decorated membrane panels [25–27], bubble meta-screens
36 [28, 29], Helmholtz [19, 22, 26, 30, 31] and coiled-up [15, 17, 32–34] resonators arrangements,
37 among others. Of particular interest is the phenomenon of slow sound [23, 35, 36], resulting from
38 the strong dispersion around the resonances of the system. It allows both the sound speed and the
39 inherent losses to be adjusted simply by changing the geometry and properties of the resonators.

40 Diffusion control using metasurfaces [37] has also attracted much interest and, in particular,
41 Jimenez *et al.* have designed a metadiffuser based on Helmholtz resonators (HRs) capable of
42 controlling the phase of the reflection coefficient of a surface and thus modifying the diffusion
43 pattern [38]. An experimental proof of this design was recently performed by Ballesterro *et al.*
44 [12, 39].

45 Despite all this research based on slow sound, realistic applications, especially in the time
46 domain, have not been thoroughly studied.

47 In this work, we propose to study analytically and numerically, to design and fabricate, and
48 then to experimentally validate a delay line device allowing to time-delay a pulse. We first outline
49 the paradigm underlying this work and study the influence of the geometry on the effective and
50 scattering properties of the system. We then discuss the challenge of temporal propagation in such

51 metamaterials and explain the design strategy employed. Finally, we show numerical simulation
 52 and experimental results of our delay line for three different configurations.

53 The idea behind this work is to propose a device to be placed on the walls of a room as sketched
 54 in Fig. 1, allowing to give a sound sensation of a room larger than it really is, **which is also referred**
 55 **to as an acoustic mirage by Norris [40]**. In other words, we seek to control the phase ϕ_R of the
 56 reflection coefficient R , and thus to be able to tune the apparent group delay τ_g

$$57 \quad \tau_g(\omega) = -\frac{d}{d\omega}\phi_R(\omega), \quad (1)$$

58 with ω being the angular frequency.

59 Since a pulse is by definition finite in time, its frequency content spreads to some extent. Thus,
 60 in order for the metasurface to delay the pulse without distorting it significantly, it must have a
 61 near-constant group delay, i.e., a near-linear phase, over the bandwidth of the pulse.

62 For this purpose, we consider a metasurface composed of Helmholtz resonators mounted in
 63 parallel to a slit opened to the room and backed by a rigid wall. For sake of simplicity, we show
 64 here a 1D situation consisting of 2 different HRs of dimensions given in Fig. 1(b) and Tab. I, placed
 65 in a square cross-sectional impedance tube of width $w_{ex} = 149$ mm. The walls of the impedance
 66 tube being rigid, i.e., Neumann condition applies, the considered configuration is equivalent to an
 67 infinite symmetric repetition of the unit cell as depicted in Fig. 1(b).

68 The strong dispersion generated in the slit above the resonators allows careful monitoring
 69 of the real and imaginary parts of the wavenumber $k(\omega)$, and thus of the group velocity $c_g =$
 70 $d\omega/d\text{Re}\{k(\omega)\}$ and dissipation ($\propto \text{Im}\{k(\omega)\}$).

71 The dispersion by a 1 HR unit cell is calculated in steady state by the transfer matrix method
 72 (TMM) [41] and depicted in Fig. 2 (a-b) by the dotted lines. This dispersion relation does not
 73 account for the finite size of the system under study since it is derived directly from the transfer
 74 matrix elements of a single unit cell. The finite size effects of the system can be seen by addition-
 75 ally calculating the reflection and transmission coefficient of the entire device and then deriving
 76 the effective properties (see [41] for more details). The effective wave number and group velocity
 77 derived from the scattering parameters are thus shown in Fig. 2 (a-c). It is worth noting here,
 78 that the rigid backing, i.e., $\partial p/\partial x = 0$, imposes a mirror symmetry. The effective medium corre-
 79 sponding to a rigidly backed system of N resonators is equivalent to an effective medium of $2N$
 80 resonators in transmission.

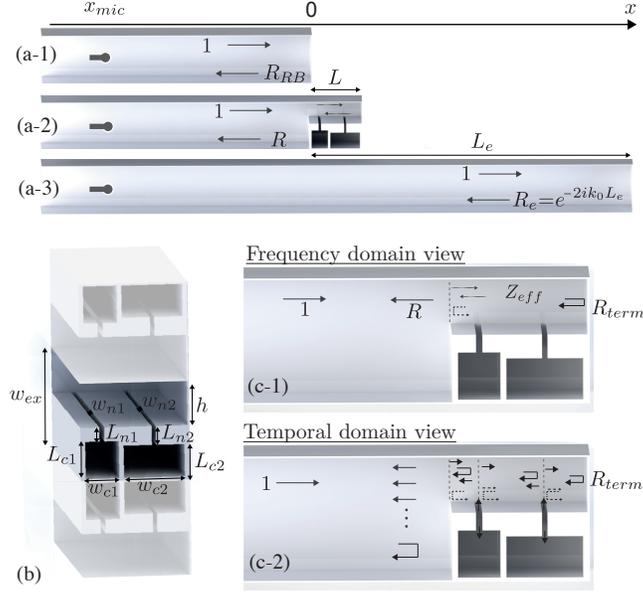


FIG. 1. (a) Schematics of the different configurations measured in a square cross-section impedance tube of width w_{ex} , in which a plane wave is impinging from the left and is reflected on a rigid wall: (a-1) configuration without the metadvice, i.e., empty tube, (a-2) configuration with the metamaterial of length L placed at the end of the rigidly backed tube, and (a-3) target configuration to be reproduced with the metamaterial. (b) Geometrical dimension of the Helmholtz resonators. (c) Differences between the permanent/frequency regime view and the temporal propagation view.

81 The slow sound phenomenon, which is driven by the resonator geometry, is clearly visible in
 82 Fig. 2 (c), with a subsonic group velocity in the static limit ($\omega \rightarrow 0$) and decreasing until the stop
 83 band above the HR resonance (colored in gray). In parallel, the dissipation increases near the
 84 stop band of the system, as shown by the large imaginary part of the wavenumber in Fig. 2 (b).
 85 For a given geometry, i.e., resonance frequency, we are therefore able to work with a given group
 86 velocity and amount of loss, just by selecting the frequency.

87 The phase of the metasurface reflection coefficient is plotted with the group delay in Fig. 2 (d-e)
 88 for $N = 1$ or 2 identical resonators (dashed and dotted-dashed black lines). Each resonator gives
 89 rise to a -2π phase jump and a group delay peak at frequencies corresponding to the Fabry-Perot
 90 resonances of the finite-depth structure. The case of two detuned resonators is also represented
 91 by the red solid lines. Although the periodicity is broken, we still have the same behavior with
 92 two group delay peaks at frequencies related to the resonance frequency of each resonator. The
 93 choice of different resonators thus facilitates the design of a metasurface with a quasi-flat group

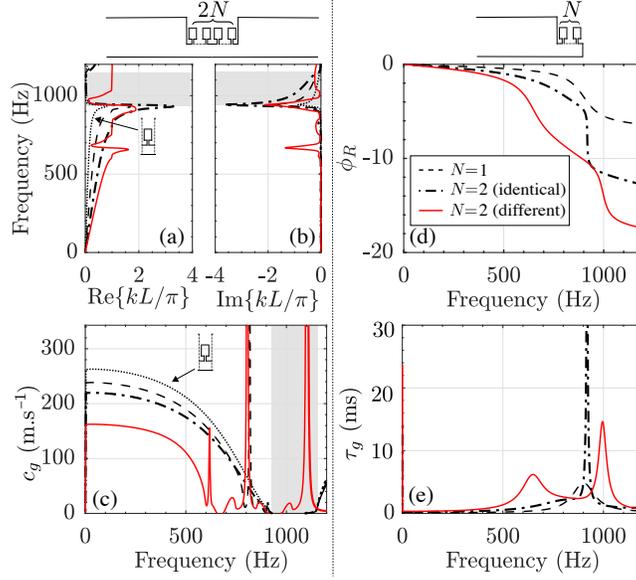


FIG. 2. [Color online] Analytically calculated effective properties of the metasurface. (a) Real and (b) imaginary parts of the normalized dispersion relation, and (c) effective group velocity. The dotted lines represent the one unit-cell effective parameters (infinite device) while the dashed, dotted-dashed and red solid curves represent the effective parameters accounting for the finite size of the device, respectively for $N = 1$, $N = 2$ with two identical unit cells, and $N = 2$ with two different HRs. (d) Phase of the reflection coefficient and (e) group delay in the rigidly backed configuration.

94 delay. The two group delay maxima are located in the vicinity of the open stop bands above the
 95 resonance frequency of each different HR. Note here that the sharp peaks in Fig. 2 (c) result from
 96 the inverse of the partial derivative of the non-zero flat wavenumber ($c_g = d\omega/d\text{Re}\{k\}$), due to the
 97 folding of the dispersion relation, in the frequency ranges between the stop bands. These regions
 98 are therefore also highly dissipative (see Fig. 2 (b)). A compromise must be found to reproduce
 99 both the right amount of loss and the time delay of a propagation over the target length.

100 Although effective properties and total reflectance are a good way to model and design struc-
 101 tures in the steady state (as generally done for metamaterials and metasurfaces), they are not
 102 suitable for the time domain, as they do not account for the first reflection interferences of the
 103 transient regime required to reach the steady state. Under the steady-state condition (frequency-
 104 domain view), the design strategy would consist to impose both an impedance matching condition
 105 and a target group delay over a given frequency range by controlling the effective impedance and
 106 total reflection. Impedance matching ensures that all of the incident wave will be transmitted

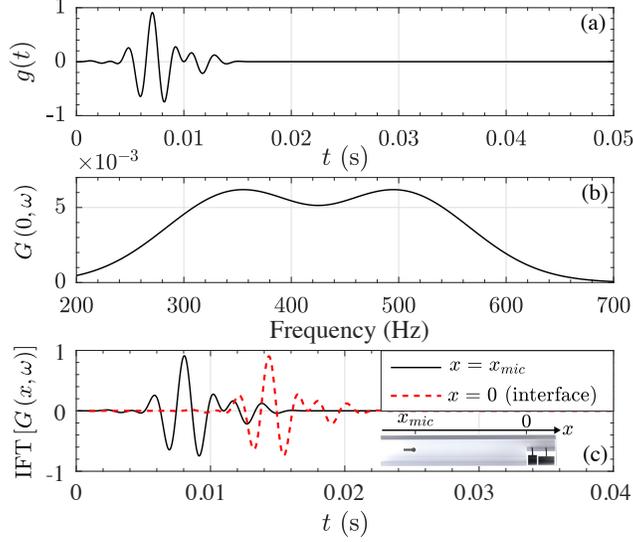


FIG. 3. [Color online] Pulse under consideration: (a) temporal signal of the pulse, (b) spectral content, and (c) propagated pulse at $x = x_{mic} = -2.6$ m, black solid line, and at the interface $x = 0$, red dashed line.

107 into the slit, propagate with a low group velocity, be reflected back by the rigid wall, and prop-
 108 agate back. The wave is therefore efficiently time-delayed due to the slow sound, as illustrated
 109 in Fig. 1 (c-1). In contrast, treating the time domain requires considering the reflection at each
 110 interface that are hidden in frequency calculations since only the total reflection is considered. In
 111 particular, the mere presence of a cross-section change at $x = 0$ generates a first direct reflection
 112 which cannot be delayed in time, as the reflected energy does not enter the metasurface.

113 Therefore, the design strategy adopted here is to optimize the geometry directly in the time
 114 domain for a given time propagating pulse and to use destructive interferences to minimize un-
 115 wanted reflections (direct reflection at $x = 0$ and coda) and to maximize desired reflections in
 116 order to preserve the shape of the delayed pulse.

117 The considered pulse, see Fig. 3 (a), consists of a combination of two cosine-modulated Gaus-
 118 sian pulses with carrier frequencies 350 Hz and 500 Hz. The metasurface must therefore be ef-
 119 ficient on the challenging low frequency range shown in Fig. 3 (b). We can then calculate the
 120 propagated pulse via an Inverse Fourier Transform (IFT) of the initial pulse multiplied by the total
 121 reflection coefficient sought R . As an example, we show on Fig. 3 (c) the pulse at the microphone
 122 position (black line) and at the interface ($x = 0$) after a propagation on a length of $x_{mic} = 2.6$ m
 123 (red dotted line).

124 To mimic the propagation of the $g(t)$ pulse over a length L_e with our device, we optimize

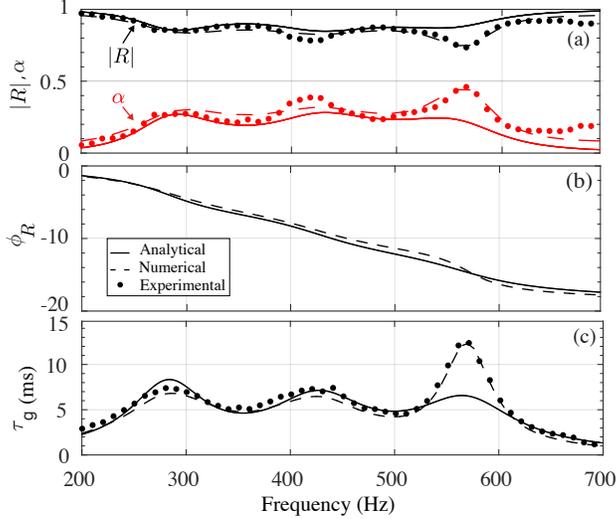


FIG. 4. [Color online] Steady state scattering properties of the metasurface optimized to reproduce a $L_e = 1$ m. (a) Reflection magnitude (black) and absorption coefficient (red), (b) phase of the reflection coefficient, and (c) apparent group delay. Solid lines represent the analytical results (TMM), dashed lines the numerical results, and dots the experimental results.

125 the geometry of its resonators by minimizing the difference between the target delayed pulse
 126 IFT $[G(\omega) e^{-2ik_0 L_e}]$ and the propagated pulse in the metasurface, modeled by its total reflection
 127 coefficient calculated by TMM, i.e., IFT $[G(\omega) R_{\text{TMM}}]$, where $G(\omega) = \text{FT}(g(t))$.

128 Figure 4 illustrates the steady-state scattering properties of the optimized metasurface repro-
 129 ducing a distance of 1 m and the corresponding group delay. The dimensions of the 16 cm thick
 130 metasurface of the optimized geometry are given in Tab. I. A twofold procedure is used to validate
 131 the TMM modeling. On the one hand, we numerically model the metasurface with a 3D finite
 132 element model using the viscothermal module of COMSOL Multiphysics software. A fine mesh
 133 is required for the boundary layers of all the rigid walls (cavity, neck, slit) to account for the vis-
 134 cothermal losses in the device with good accuracy. On the other hand, an experimental validation
 135 is performed. The metasurface is machined with 3 mm thick aluminum plates and is placed in a
 136 $w_{ex} = 149$ mm square impedance tube with a rigid backing. The scattering properties are recov-
 137 ered from the measurement of the microphone-to-speaker frequency responses at 4-microphone
 138 positions. The agreement between the analytical (solid), numerical (dashed line), and experimen-
 139 tal (dots) results is very good, thus validating our analytical modeling used for the optimization
 140 process. The slight discrepancies visible around 580 Hz can be attributed to the length correction
 141 modeling for the Helmholtz resonators (see [41]).

142 Figure 5(a-3) shows the numerically simulated and experimentally measured outgoing temporal
 143 wave from the device. As expected and predicted by the analytical results given in Fig. 5 (a-2),
 144 the pulse is effectively delayed by 5.8 ms. This delay, highlighted by the gray horizontal arrow,
 145 corresponds to the time difference between the pulse after propagation in the metasurface and after
 146 reflection at the interface (metasurface replaced by a rigid backing at $x = 0$) shown respectively
 147 in Figs. 5 (a-3,4). Slight discrepancies are visible at the starting and end of the pulse (both in
 148 the experiments and in the simulations) and are due to several unavoidable limitations. First,
 149 although the optimization is performed over a frequency region where the dispersion is small,
 150 the Helmholtz resonator metasurfaces remain dispersive, as shown by the non-perfectly constant
 151 group delay in Fig. 5 (a-1). Second, destructive interference with early and late reflections cannot
 152 perfectly result in total wave cancellation. In addition, due to the viscothermal losses inherent
 153 to Helmholtz resonators, the amplitude of the pulse is slightly reduced. Finally, the second pulse
 154 visible in Fig. 5 (a-4) is due to the reflection on the rigid wall around the loudspeaker. Nevertheless,
 155 most of the energy remains concentrated on the targeted pulse and therefore has the potential to
 156 give the overall good feeling of a delayed pulse.

157 From the optimized geometry of the 1 m configuration, we then optimize the geometry to
 158 reproduce two other propagation distances $L_e = 0.75$ m and $L_e = 0.6$ m, by changing only the
 159 cavity widths w_c by a factor 0.611 and 0.42 respectively. The device thicknesses for these two
 160 configurations are therefore $L = 9.8$ cm and $L = 6.6$ cm respectively. The dimensions of the three
 161 configurations are given in Tab. I and the results are given in Figs. 5 (b-c). In each case, the
 162 optimal geometry delays the pulse by the correct time delay, $\tau_g = 4.4$ ms and 3.5 ms respectively.
 163 We can see that the steady state group delay of the optimized geometry corresponds to these values
 164 at frequencies 350 and 500 Hz, i.e., the two carrier frequencies of the pulse. Although the pulse
 165 is distorted more significantly when we linearly reduce the geometry from the first configuration,
 166 the shape and location of the pulse matches the target values. Note again here that the second
 167 pulse visible in the last row of subplots is solely due to the experimental setup. The left side of the
 168 impedance tube, on which the source is mounted, is not anechoic, which leads to a back reflection
 169 of the reflected pulse.

170 In conclusion, we have analytically designed in this work a metasurface capable of temporally
 171 delaying a pulse. This sub-wavelength device is able to mimic a propagation over a distance much
 172 larger than its thickness L , i.e., $L_e \approx 6.25L$ for the first configuration, $L_e \approx 7.8L$ for the second,
 173 and $L_e \approx 9L$ for the third configuration and could be reconfigurable, since a linear modification

Configurations	w_{ex}	h	w_{c1}	L_{c1}	w_{n1}	L_{n1}	a_1	w_{c2}	L_{c2}	w_{n2}	L_{n2}	a_2
HRs, dispersion relation	149 mm	68.8 mm	21.4 mm	29.1 mm	13.1 mm	45.2 mm	25.5 mm	46.7 mm	11.9 mm	2.5 mm	61.2 mm	60.7 mm
Config.1 - $L_e = 1$ m	149 mm	65.8 mm	51.3 mm	56.7 mm	7.8 mm	57 mm	92.7 mm	49.5 mm	28.7 mm	6.6 mm	28.7 mm	102.9 mm
Config. 2 - $L_e = 0.75$ m	149 mm	65.8 mm	31.3 mm	56.7 mm	7.8 mm	37 mm	56.6 mm	49.5 mm	28.7 mm	6.6 mm	28.7 mm	66.8 mm
Config. 3 - $L_e = 0.6$ m	149 mm	65.8 mm	21.6 mm	56.7 mm	7.8 mm	27.3 mm	38.9 mm	49.5 mm	28.7 mm	6.6 mm	28.7 mm	49.1 mm

TABLE I. Dimensions of the metasurface for the different configurations considered.

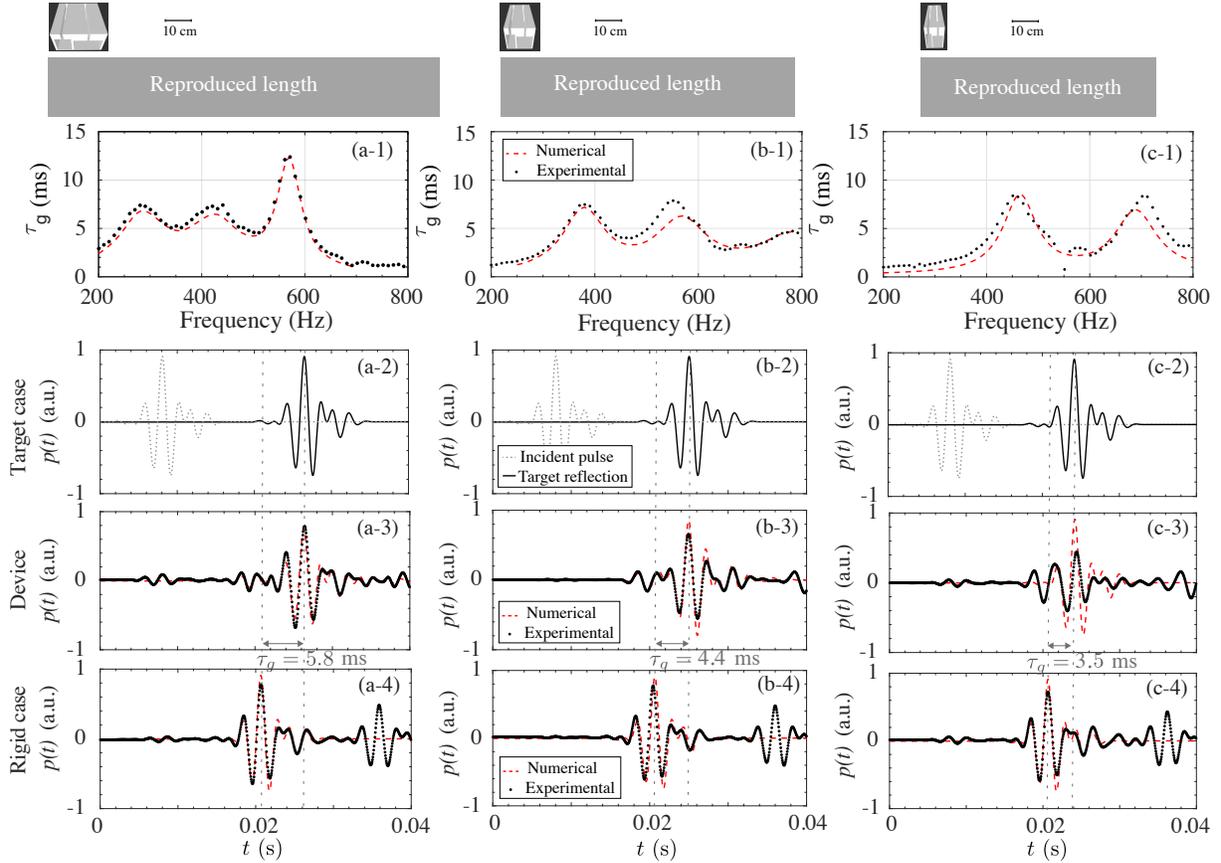


FIG. 5. [Color online] Metasurface delayed pulse for the 3 configurations considered: $L_e = 1$ m (a), 0.75 m (b), and 0.6 m (c).

(-1) steady state group delay, (-2) incident and target pulse (analytical), (-3) measured and simulated pulse delayed by the metasurface, and (-4) measured and simulated pulse reflected off a rigid wall (without metasurface). The red dashed lines and black dots represent the full-wave simulation and experimental results, respectively. The solid black lines represent the analytical target, and the thin black dotted lines the incident pulse.

174 of an initial geometry can reproduce several distances. As room acoustics application requires to
175 account for the multiple reflections at each interface, the geometry optimization is performed by
176 minimizing in the time domain the difference between the targeted pulse (propagation over a dis-
177 tance L_e) and the pulse after propagation in the metasurface of reflection coefficient R , determined
178 from the TMM. We validated our analytical predictions both numerically and experimentally. We
179 found that all three configurations reproduce well the correct group delay at the two carrier fre-
180 quencies of the considered pulse and thus that the center of the pulse corresponds well to that of
181 the target. Small discrepancies at the beginning and end of the delayed pulses, due to unavoidable
182 dispersion and unwanted reflection, are found. However, since most of the energy of the pulse
183 is concentrated in its center, which matches well with that of the target, the device could provide
184 the sound feeling of the delayed pulse. In terms of prospects, a reconfigurable accordion device
185 could be fabricated and the bandwidth of the working frequency could be extended, for example,
186 by adding multiple slits in parallel.

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249 dispersion relation from a single unit cell, as well as the effective wave number to, and presents the
250 experimental results obtained from the optimized geometry of two other configurations reproducing a
251 distance of 0.75 m and 0.6 m..