Giant Acoustic Concentration by Extraordinary Transmission in Zero-Mass Metamaterials
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We demonstrate 97%, 89%, and 76% transmission of sound amplitude in air through walls perforated with subwavelength holes of areal coverage fractions 0.10, 0.03, and 0.01, respectively, producing 94-, 950-, and 5700-fold intensity enhancements therein. This remarkable level of extraordinary acoustic transmission is achieved with thin tensioned circular membranes, making the mass of the air in the holes effectively vanish. Imaging the pressure field confirms incident-angle independent transmission, thus realizing a bona fide invisible wall. Applications include high-resolution acoustic sensing.

The pioneering work by Ulrich and by Ebbesen et al. [1,2] on the extraordinary optical transmission (EOT) through a lattice of subwavelength holes has inspired extensive studies on the transmission properties of electromagnetic waves through tiny apertures of various shapes and decorations [3–7]. Our proposed new mechanism for extraordinary transmission involves making the effective mass of the air column disappear by introducing a thin membrane. Metamaterials consisting of arrays of thin membranes were reported to exhibit tunable density [8–12]. We therefore install tensioned membranes across the holes, so that the air column and membranes form a metamaterial structure equivalent to a unit cell of the system described in Refs. [9, 10]. We first tested the transmission characteristics of a one-hole rigid circular wall with the setup of Fig. 1(a). Midway along a circular tube of length 2.3 m and 100-mm inner diameter we set a 5-mm thick aluminum wall with a 17-mm diameter hole at its center. This corresponds to a filling factor (i.e., areal coverage fraction) \( \alpha = \pi r^2/A = 0.03 \). On resonance, most of the acoustic energy is strongly reflected from the wall with the hole, but with the membrane in place no detectable reflection was observed; much of the incident energy is funneled into the small hole covering only 3% of the wall area, giving a particle velocity inside the holes 31 times greater than that of the incident wave. In other words, there is a \((lT^2/\alpha^2 \sim 950)\)-fold energy density intensification in the hole. This remarkably high experimental value is around 2 orders of magnitude better than the previous record in acoustics [13]. The use of a zero effective mass stemming from the membrane has greatly improved the efficiency.

We constructed an array of four holes drilled along the bisecting line of a rectangular rigid acrylic plate of thickness 5 mm, as shown in Fig. 2(a), placed in a rectangular cross-sectional duct. This setup accommodates two-dimensional (2D) plane waves generated by an array of four speakers at the duct entrance, as can be seen from top-view schematics in Fig. 2(a). The filling factor of the four-hole plate, \( \alpha = 0.03 \), was fixed by the choices \( r = 8.5 \) and \( d = 88.6 \) mm, respectively, where \( d \) is the array period. The wall was first installed perpendicular to the direction of incidence (incidence angle \( \theta = 0^\circ \)). Figure 2(b) shows the measured instantaneous 2D pressure distributions at 1.20 kHz for the three cases of no wall, wall with bare holes, and perforated wall with resonantly vibrating membrane-covered holes (from top to bottom, respectively), obtained using a scanned probe microphone near the top of the duct. The wall with the bare holes seriously hinders the transmission, but with the membrane installed the transmission becomes, as expected, almost as good as with no wall.

In conclusion, we realize zero-mass metamaterials by making the inerterance of membrane-covered air holes close to zero. We thereby experimentally and theoretically demonstrate a
new mechanism for acoustic extraordinary transmission. For a filling fraction of 1% we obtain a 57% transmission intensity; this implies that on resonance the particle velocity inside a hole is 76 times greater than that of the incident wave, corresponding to an intensification of the acoustic energy density by the giant factor of 5700. Such a high concentration of acoustic energy into a small hole of radius $r = \lambda/56$ enables sensitive detection of acoustic signals with subwavelength resolution: in optics, such subwavelength intensity concentration is used in scanning near-field optical microscopy [3], and the present work not only opens the way to the efficient realization of its acoustic counterparts in fluid ultrasonics and underwater acoustics, but also to the analogous realization in solid-state ultrasonics.

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References