Technology Reports

Prototype of Mobile Super Directional Loudspeaker

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A prototype of a super directional loudspeaker to be mounted on a mobile terminal-sized box was built, and its acoustic characteristics were measured. Thus, the possibility of a phone call having a high level of privacy, and providing stereo and 3D audio services of high-level quality with a high degree of channel separation are presented.

1. Introduction

Along with expanding mobile communication services and additional mobile terminal functions, the services of providing spoken and musical forms of listening enjoyment are also becoming popular. Such audio content is generally being listened to through the loudspeakers of mobile terminals, while characters and images are viewed on a display. One of the problems posed when listening in such a mobile communication environment is that the reproduced sound is sometimes diffused into the surrounding area. Even though headphones or earphones offer an alternative means, such use is not the currently preferred method. Research is now being conducted on technologies used to reproduce a sound field[*1] through several loudspeakers so that the sound field is controlled [1]. A super directional[*2] loudspeaker that forms a beam-shaped sound field by utilizing ultrasonic waves has also been proposed [2]-[4].

Research on the super directional loudspeaker has been conducted for many years from both theoretical and experimental standpoints. A report on the acoustic characteristics of a super directional loudspeaker [5], a proposed modulation method of reducing distortion [6], and a report on an experimental digital modulator unit based on this proposal [7] have been released. Moreover, practical application has been examined [8], and by

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*1 Sound field: In this article, a space where audible sound waves exist.

*2 Directional: A characteristic whereby the amplitude of an electromagnetic wave, optical wave, sound wave, or other wave is higher in a specific direction. Generally, for a sound wave, the larger the vibrating face of a loudspeaker or the higher the frequency, the higher the directivity becomes.

improvement of electroacoustic transducer efficiency[*3], a commercial product has also been recently released [9]. Such developments have been applied to relatively large loudspeakers [9], however, and a super directional loudspeaker that can be carried by users has yet to be examined. Conversely, a super directional loudspeaker having a relatively small diameter by utilizing a short wavelength ultrasonic wave is suitable for mounting on a mobile terminal.

This article examines utilization modes for a super directional loudspeaker in the mobile communication environment and describes its usefulness. We also describes the experiment results of the acoustic characteristics of the super directional loudspeaker mounted on a mobile terminal-sized box, and future tasks.

2. Structure of Super Directional Loudspeaker

A super directional loudspeaker, also called a parametric loudspeaker, forms a sound field having high directivity by utilizing a virtual sound source (parametric array) caused by the non-linearity[*4] of air, and human sense of hearing. **Figure 1** shows the principle of a super directional loudspeaker. An ultrasonic carrier wave with high frequency exceeding 20 kHz that cannot be perceived by the human sense of hearing is amplitude-modulated by an audio signal such as voice or music. The loudspeaker radiates the modulated wave having large amplitude that causes the non-linearity of air. In the process of modulated wave propagation through the air, a quadratic distortion[*5] is generated by the non-linearity of air. This quadratic distortion is generated along the sound field of the modulated wave having a short wavelength and high directivity, and becomes a virtual sound source. The sound of the ultrasonic frequency band cannot be perceived by the human sense of hearing, and only the signal within the audible frequency range[*6] included in the quadratic distortion is demodulated and becomes audible.

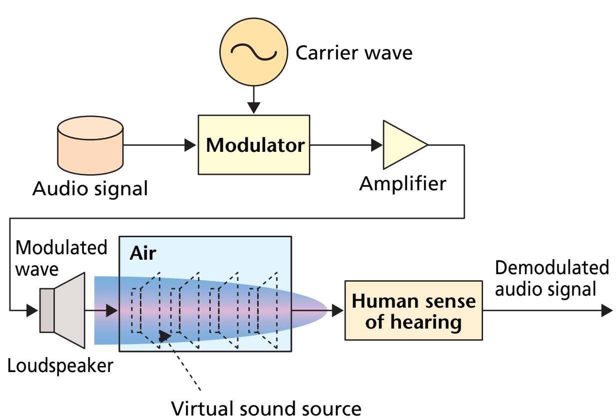


Figure 1 Principle of super directional loudspeaker

3. Utilization Modes of Super Directional Loudspeaker in Mobile Communication Environment

Conventional loudspeakers mounted on mobile terminals have a small diameter and vibrate air directly by using an audio signal with a long wavelength so that the reproduced sound is highly diffused as shown in **Figure 2** (a). Conversely, when a super directional loudspeaker is mounted on a mobile terminal as shown in Fig. 2 (b), it is possible to make the reproduced sound inaudible to someone near the user.

Moreover, people are beginning to use services that reproduce stereo or 3D audio signals using multiple loudspeakers on mobile terminals. However, loudspeakers that produce highly diffusive sound tend to generate crosstalk, where one ear hears a sound wave mixed with one from the other loudspeaker not directed to this ear as shown in **Figure 3** (a). Accordingly, it is difficult to control a reproduced sound field, thus confining the optimum sound receiving position. On the contrary, it is believed that by forming a highly directional sound field for each ear using multiple super directional loudspeakers, crosstalk can be reduced as shown in Fig. 3 (b) and the reproductions of stereo or 3D audio signals can be realized with high accuracy. Moreover, since a beam-shaped sound wave can be reproduced, it is possible to ensure a wider optimum sound receiving position in both backward and forward directions.

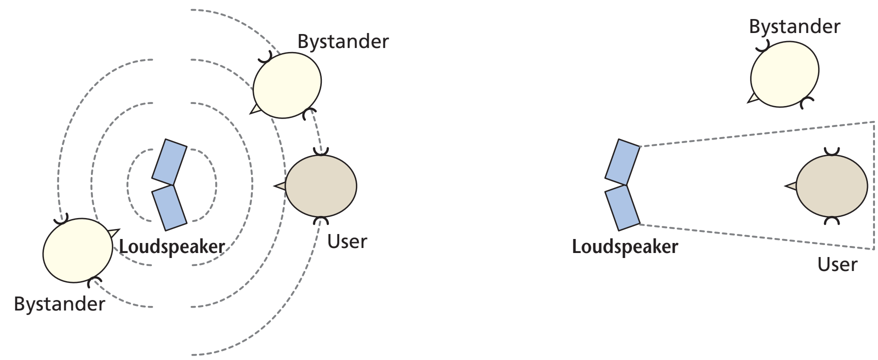
When mobile terminals become smaller than existing ones, the use of a loudspeaker not mounted on the mobile terminal but installed on a wall or ceiling instead can be considered as shown in **Figure 4**. When the mobile terminal held by a user determines the position of the user, a super directional loudspeaker

*3 Electroacoustic transducer efficiency: The efficiency of converting an electrical signal into an acoustic signal.

*4 Non-linearity: In this article, a characteristic whereby a signal having a frequency other than the input signal frequency is generated. For example, a characteristic when a sine wave of 1 kHz is input to a loudspeaker, two or three times of the input signal frequency is generated.

*5 Quadratic distortion: The frequency component of an output signal having a frequency that is two times that of the input frequency. For example, a frequency component of 2 kHz of an output signals, when a sine wave of 1 kHz is input to a loudspeaker.

*6 Audible frequency range: The frequency range of sound that can be perceived by the human sense of hearing. Generally, 20 Hz to 20 kHz.

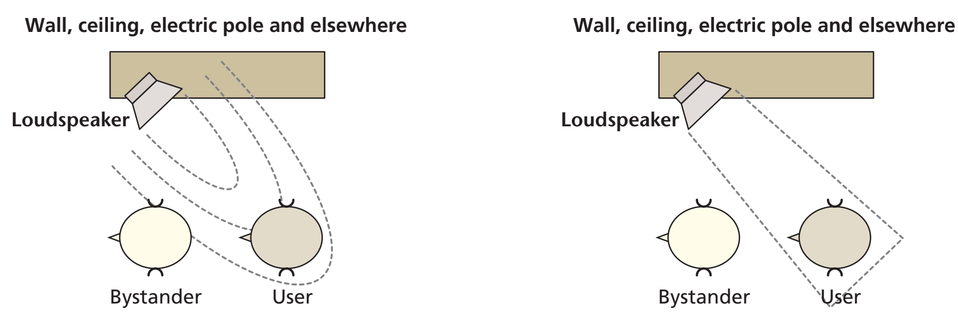


(a) Reproduction by conventional loudspeaker (b) Reproduction by super directional loudspeaker

Figure 2 Sound reproduction by loudspeaker mounted on mobile terminal

(a) Reproduction by conventional loudspeaker (b) Reproduction by super directional loudspeaker

Figure 3 Sound reproduction for left and right ears using two loudspeakers mounted on mobile terminal



(a) Reproduction by conventional loudspeaker (b) Reproduction by super directional loudspeaker

Figure 4 Sound reproduction toward moving user via external loudspeaker

directed toward the user reproduces a highly directional sound field that is inaudible to people nearby. We believe that since mobile terminals will be further miniaturized, the reproduction of super directional sound fields from acoustic equipment installed on walls, ceilings and elsewhere will become increasingly important.

This article, in considering the utilization modes shown in Fig. 2 (b) and Fig. 3 (b), describes the prototype of two super directional loudspeakers to be mounted on a mobile terminal-sized box that we built, along with the measurement results of acoustic characteristics.

4. Prototype of Mobile Super Directional Loudspeaker

4.1 Requirements for Mounting on a Mobile Terminal

In order to mount a super directional loudspeaker on a commercial mobile terminal, the conditions listed in **Table 1** are required to be satisfied, in consideration of the specifications and characteristics of loudspeakers mounted on existing mobile terminals. When the sound pressure at a listening position becomes 140 dBSPL (Sound Pressure Level)*7 or higher, a problem may occur whereby audibility is temporarily reduced, for example [10]. However, a super directional loudspeaker is usually necessary to radiate sound with high sound pressure in order to generate the non-linearity of air.

4.2 Specifications of Prototype

In order to examine the acoustic characteristics and possibility of services for a mobile terminal on which a super directional loudspeaker is mounted, we built a prototype. **Table 2** lists the specifications of this prototype shown in **Photo 1** (a). The commercially available power supply, modulator, and amplifier used are installed separately from the prototype. As shown in Photo 1 (a), the prototype is small enough to be held in the hand. The prototype includes two independent loudspeakers installed at both ends of the box for reproducing stereo or 3D signals. Each loudspeaker channel consists of 16 piezoelectric transducers*8 that are densely mounted to increase radiation efficiency. Moreover, by providing a hinge mechanism*9 at the center of the box to make a folding type unit, the directions of the radiating faces of the loudspeakers can be adjusted. As a result, when a user holds the box in front of his/her face at a distance of several dozen centimeters, each loudspeaker can be directed toward the corresponding ear as Photo 1 (b).

Table 1 Required conditions

Integrated devices	Power supply, modulator, amplifier, and loudspeaker
Power consumption	1 W or lower
Sound pressure of modulated wave	140 dBSPL or lower
Sound pressure of demodulated wave	70 dBSPL or higher

Table 2 Specifications of prototype

Number of loudspeakers	2 channels
Number of transducers	16 per channel
External dimensions (W×H×D)	About 250×65×20 mm

(a) Radiating face side

(b) Usage example

Photo 1 Prototype of mobile super directional loudspeaker

5. Acoustic Characteristics

5.1 Characteristics in a Free Sound Field

First, the acoustic characteristics of one loudspeaker channel of the prototype were measured in an anechoic room, having a free sound field with little reflection and echo. **Figure 5** shows

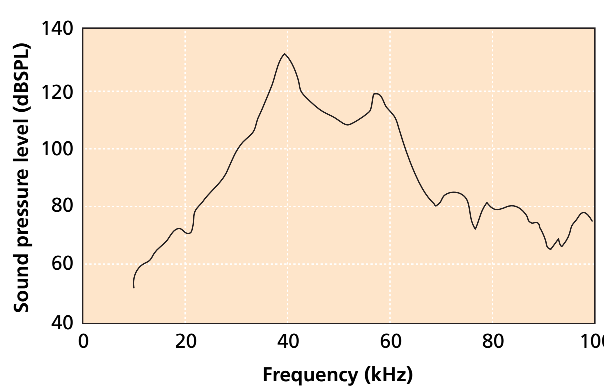


Figure 5 Sound pressure frequency response of loudspeaker

*7 dBSPL: A unit of sound pressure level. In human perception, an increase of 10 dBSPL is usually perceived as sound twice as loud. A typical conversation is about 60 dBSPL.

*8 Piezoelectric transducer: An element that utilizes a characteristic possessed such as by a crystal whereby a voltage is generated when pressure is applied, or an opposite characteristic, and is used as an oscillator circuit, filter, etc.

*9 Hinge mechanism: A structure that connects two parts together and allows opening and closing, just like a hinge. Also used in folding-type mobile terminals.

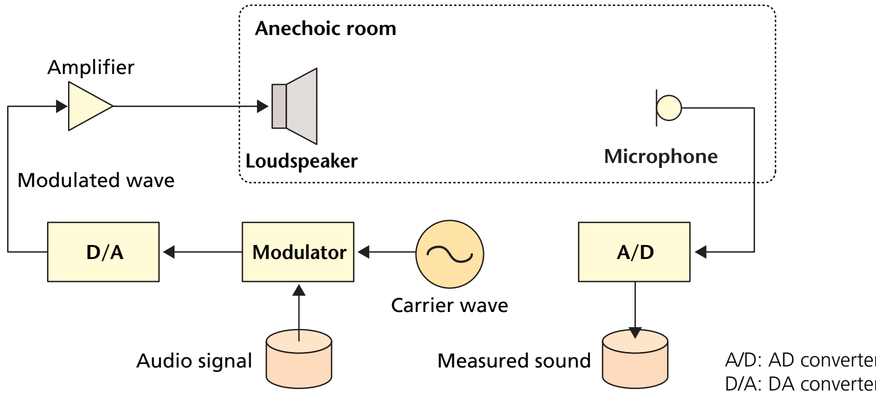


Figure 6 Measurement configuration

the sound pressure frequency response of the loudspeaker. An input voltage of 6.35 Vrms (root mean square voltage)[*10] was supplied to the loudspeaker, and measurement was performed at a distance of 50 cm on the central axis of the loudspeaker. The loudspeaker had a resonant frequency of about 40 kHz, and sound pressures of 120 dBSPL and higher were measured through a frequency band between plus and minus 3 kHz of said resonant frequency.

Next, the demodulation characteristics of the super directional loudspeaker were measured using the configuration shown in **Figure 6**. A carrier wave of 40 kHz was amplitude-modulated by an audio signal using a modulation factor[*11] of 1, and the resulting modulated wave was input to the loudspeaker for electroacoustic conversion. A microphone was used to measure the sound wave from the loudspeaker. In the sound wave measured, the one with the same frequency as the input audio signal was selected as the demodulated wave.

Figure 7 shows the sound pressure frequency response of the demodulated wave of the loudspeaker measured at a distance of 50 cm and directional angle of 0 degrees. A modulated wave with an input voltage of 10 Vrms was applied to the loudspeaker, with the same settings retained in the following steps. It was verified that the sound pressure of the demodulated wave was approximately flat at around 70 dBSPL in a bandwidth of 2 to 10 kHz, and that the sound pressure tended to drop by about 10 dB when the frequency becomes one half from 2 kHz and lower. The sound pressure including that of the modulated wave

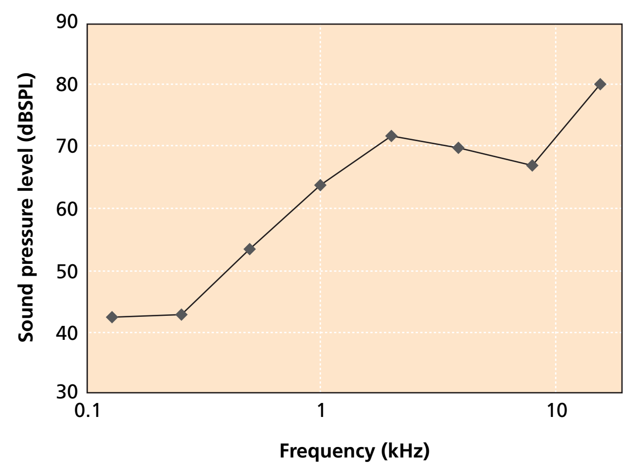


Figure 7 Sound pressure frequency response of demodulated wave

was 140 dBSPL at a distance of 25 cm and 134 dBSPL at a distance of 50 cm.

Figure 8 shows the directivity of the demodulated wave at a distance of 50 cm. As the input audio signals, single sine waves of 1 kHz, 2 kHz and 4 kHz, respectively, were used. For demodulated waves of 2 kHz and 4 kHz, the sound pressures reduced by 3 dB at an angle of 10 degrees or lower, thus indicating high directivity equal to or higher than that of each commercial super directional loudspeaker [9]. **Figure 9** shows the sound pressure spatial distribution of the demodulated wave for a sine wave frequency of 2 kHz for the audio signal. The horizontal axis indicates the distance from the central axis of the loudspeaker in the perpendicular direction; the vertical axis indicates the distance from the loudspeaker in the central axis

*10 Vrms: The root mean square value of a voltage.
*11 Modulation factor: A ratio of peak-to-peak amplitude of a modulated component to a carrier component.

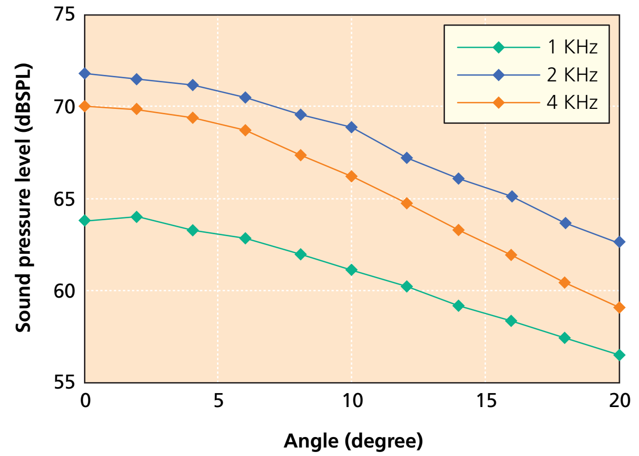


Figure 8 Directivity of demodulated wave

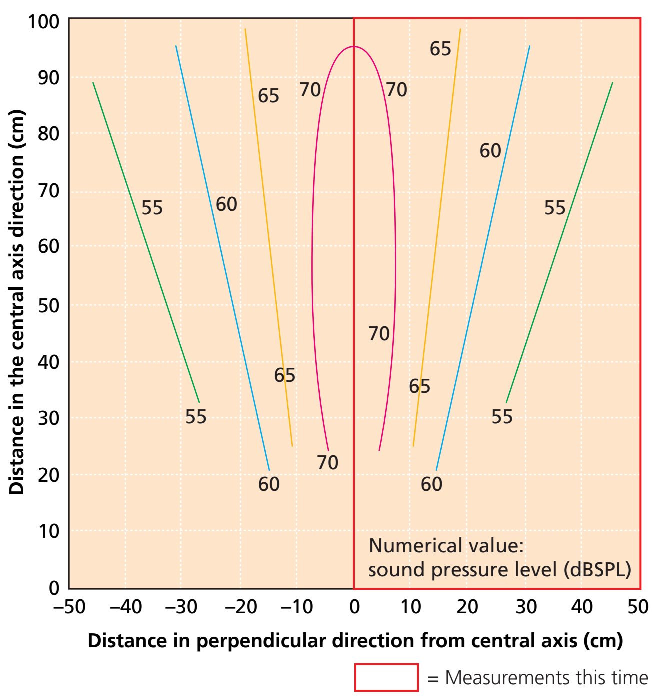


Figure 9 Sound pressure spatial distribution of demodulated wave (2 kHz)

direction. Since the transducers are arranged to be line symmetrical on the radiating face of the loudspeaker, and the sound radiated from the radiating face is assumed to be line symmetrical, the directional angles were only measured for one side with respect to the central axis of the loudspeaker radiating face. The gap between two adjacent measured points is interpolated linearly based on the assumption that sound pressure is attenuated linearly with respect to the logarithmic distance. From Fig. 9, it is possible to verify that the sound pressures of the demodulated wave are distributed along the central axis with a beam shape. Up to a distance of 90 cm from the loudspeaker, it was possible to assure that the sound pressure of the demodulated wave was 70 dBSPL or higher at a spatial distance of about 5 cm from the central axis. Up to a distance of 50 cm from the loudspeaker, a beam-shaped sound field is considered to form along the central axis when attenuated by 10 dB or higher at a distance of 20 cm from the central axis.

5.2 Acoustic Characteristics near the Ears

In order to measure the acoustic characteristics of human hearing, a Head and Torso Simulator (HATS)[*12] was used to simulate the reflection and diffraction of sound waves around the head and upper body. As shown in **Figure 10**, the loudspeaker was placed on the central axis at a distance of 50 cm in front of the HATS, and at the same height as that of both ears of the HATS. By changing angle θ, which is formed by the central axis of the HATS and central axis of the loudspeaker, the loudspeaker was rotated toward the left ear side of the HATS. Two microphones were placed near both respective ear canal entrance points of the HATS for measurement (**Photo 2**).

Figure 11 shows the angles of the loudspeaker and sound pressures of the demodulated wave at the left and right ears. The sound pressure of the demodulated wave at the left ear became a local maximum when angle θ of the loudspeaker was about 12 degrees. While the sound pressure at 2 kHz was about 75 dBSPL at the left ear, it was about 60 dBSPL at the right ear.

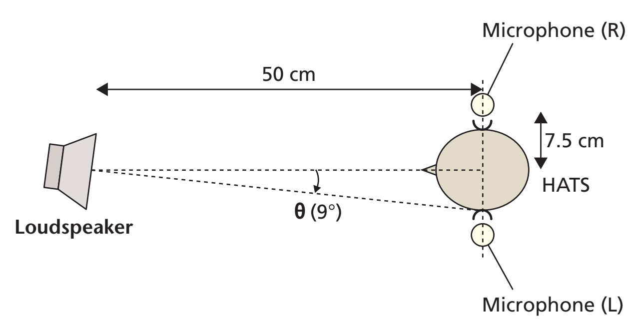


Figure 10 Placement of HATS and loudspeaker

*12 HATS: A simulator used to simulate the reflection and diffraction of sound waves around the head and body size of average adult. Standardized in ITU-T Recommendation P.58 (Head and torso simulator for telephonometry).

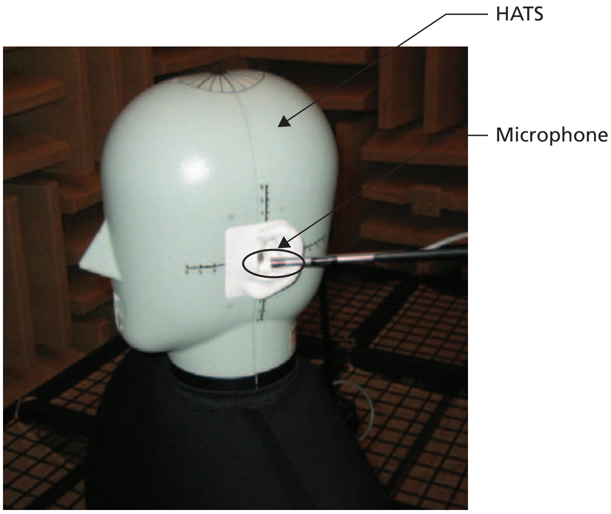


Photo 2 Placement of microphone

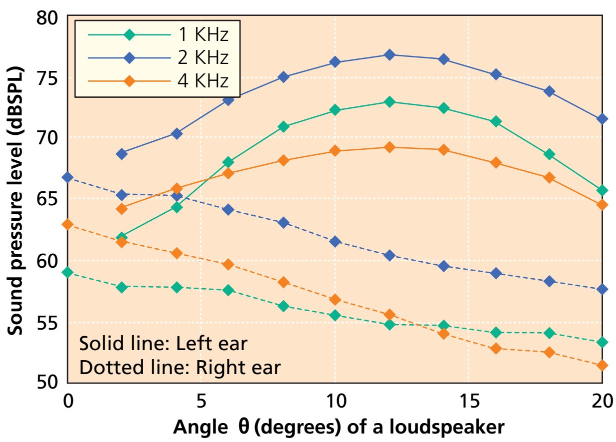


Figure 11 Angle of loudspeaker and sound pressure of demodulated wave

The degree of channel separation was about 15 dB.

Considering the fact that the difference in sound pressure between both ears is usually about 20 dB even after performing crosstalk cancellation processing when reproducing a stereo or 3D audio signal from conventional loudspeakers, such processing may become unnecessary for super directional loudspeakers.

5.3 Future Tasks

Table 3 lists the performance of the prototype based on the measurements. In order to mount the super directional loudspeaker on a mobile terminal when compared to the required conditions shown in Table 1, several conditions still remain to be satisfied. Specifically, the power supply, modulator, amplifier, and loudspeaker must be miniaturized and the power consumption reduced. In addition, the demodulation efficiency must be increased even more. We believe that the sound pressure of a demodulated wave of less than 2 kHz must also be increased to 70 dBSPL, while maintaining the demodulated wave at 140 dBSPL or lower at every position.

Table 3 Performance of prototype

Integrated devices	2 channels of loudspeakers
Power consumption	5 W or higher
Sound pressure of modulated wave	140 dBSPL or lower (further than distance of 25 cm)
Sound pressure of demodulated wave	70 dBSPL or higher (2 kHz or higher)

6. Conclusion

In order to realize a sound field having a high level of privacy in the mobile communication environment, we built an prototype of two super directional loudspeakers to be mounted on a mobile terminal-sized box, and measured the acoustic characteristics of the prototype. It was verified that the demodulated sound pressure on the central axis of the loudspeaker at a distance of around 50 cm from the loudspeaker was 70 dBSPL or higher, and that a beam-shaped sound field having high directivity was formed along the central axis while being attenuated by about 10 dB at a distance of 20 cm from the central axis. Moreover, it was also verified that a high degree of channel separation was possible where the difference in sound pressure between both ears was about 15 dB. Still, there are remaining issues to be addressed in the future for mounting super directional loudspeakers on mobile terminals, and certain conditions must be satisfied. Specifically, the equipment must be further miniaturized, power consumption reduced, radiation and demodulation efficiency improved, and the safety level increased.

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