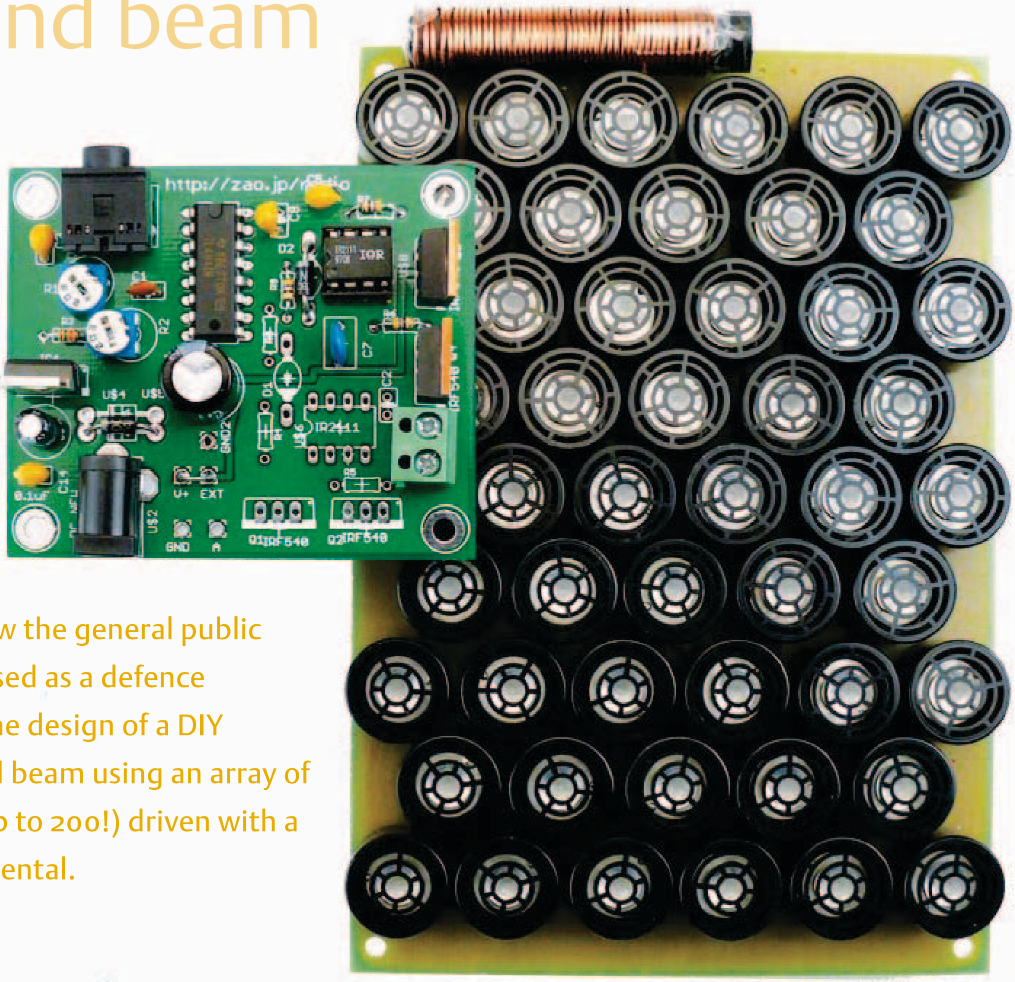
Ultrasonic Directive Speaker

50+ piezo transducers generate audible sound beam



By Kazunori Miura (Japan)

The acronym LRAD sadly and worryingly made it to newspaper stories in connection with Somali pirate attacks on vessels in the Gulf of Aden, and that is how the general public first got word of sound being used as a defence weapon. This article explores the design of a DIY 50-metre range directive sound beam using an array of piezo ultrasonic transducers (up to 200!) driven with a PWM signal, all strictly experimental.

Spurred by the success of their Long Range Acoustic Device® (LRAD) systems, American Technology Corporation changed its name to LRAD Corporation on March 25, 2010 [1]. For non military applications, Audio Spotlight® is a product of Holosonic Research Labs, Inc. [2]. Audio Spotlight produces a very sharp sound beam and has found applications in museums, exhibits and galleries. Those who hear sound from a parametric speaker for the first time are typically surprised and sometimes frightened by the effect. Sounds appear to be heard from extremely nearby, although the person standing right beside you does not hear anything.

Parametric speaker arrays typically employ ultrasonic waves, the same as used in car parking 'radars', distance meters, metal analyzers, etc. However it was not until recently that approaching a real parametric speaker is possible using commonly available components.

Principle of the parametric speaker

A parametric speaker achieves high directivity thanks to the almost line-of-sight propagation of sound waves in the supersonic range. Supersonic is often loosely defined as 'above 20 kHz' because it exceeds the upper frequency limit of human hearing. In practice, 14 kHz is commonly found to be the real limit at least for adults.

So how can humans perceive a supersonic sound wave? Several methods have been devised to convert a supersonic wave into a sound wave you can hear. One method is to passively obtain an audible frequency from two supersonic wave sources with a slightly different frequency. For example, an undulating 1 kHz tone is obtained from two supersonic waves of 40 kHz and 41 kHz. As illustrated in **Figure 1**, where two supersonic waves intersect, a sound within the audible domain is perceived. The disadvantage of this method is that only weak audible sounds are produced, by no means

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enough to stun or incapacitate people like the LRAD.

Other ways of producing an audible sound from supersonic waves include amplitude modulation (AM), double sideband modulation (DSB), single sideband modulation (SSB), frequency modulation (FM) all employ the recently developed parametric speaker system.

Inevitably, a 110 dB+ supersonic wave will be irregular in terms of sound pressure distribution as it propagates through a long air mass, and an audible sound seems to appear by itself owing to these non-linear characteristics. As a result, the audible sound perceived is marked by a fair amount of distortion, which is undesirable for 'narrowcasting' applications like in a museum. Manufacturers typically resort to signal processing using DSPs to reduce distortion to a minimum, often in combination with a highly sophisticated parametric speaker

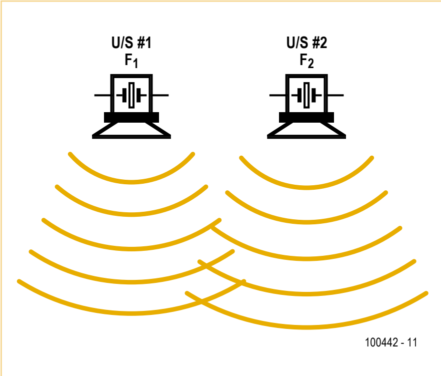

Figure 1. Where ultrasonic waves from sources with frequencies F1 and F2 intersect, audible sounds amounting to F3 = |F1–F2| may be heard.

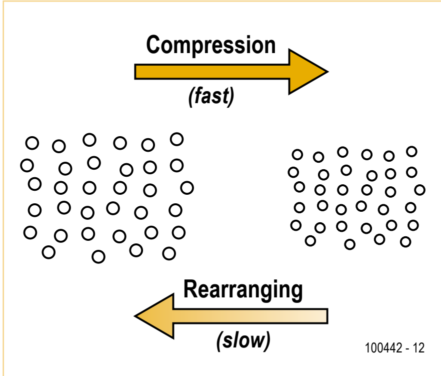

Figure 2. Shock waves come about by air molecules on their way back to their original position colliding with other molecules being compressed at the same time by a sound wave.

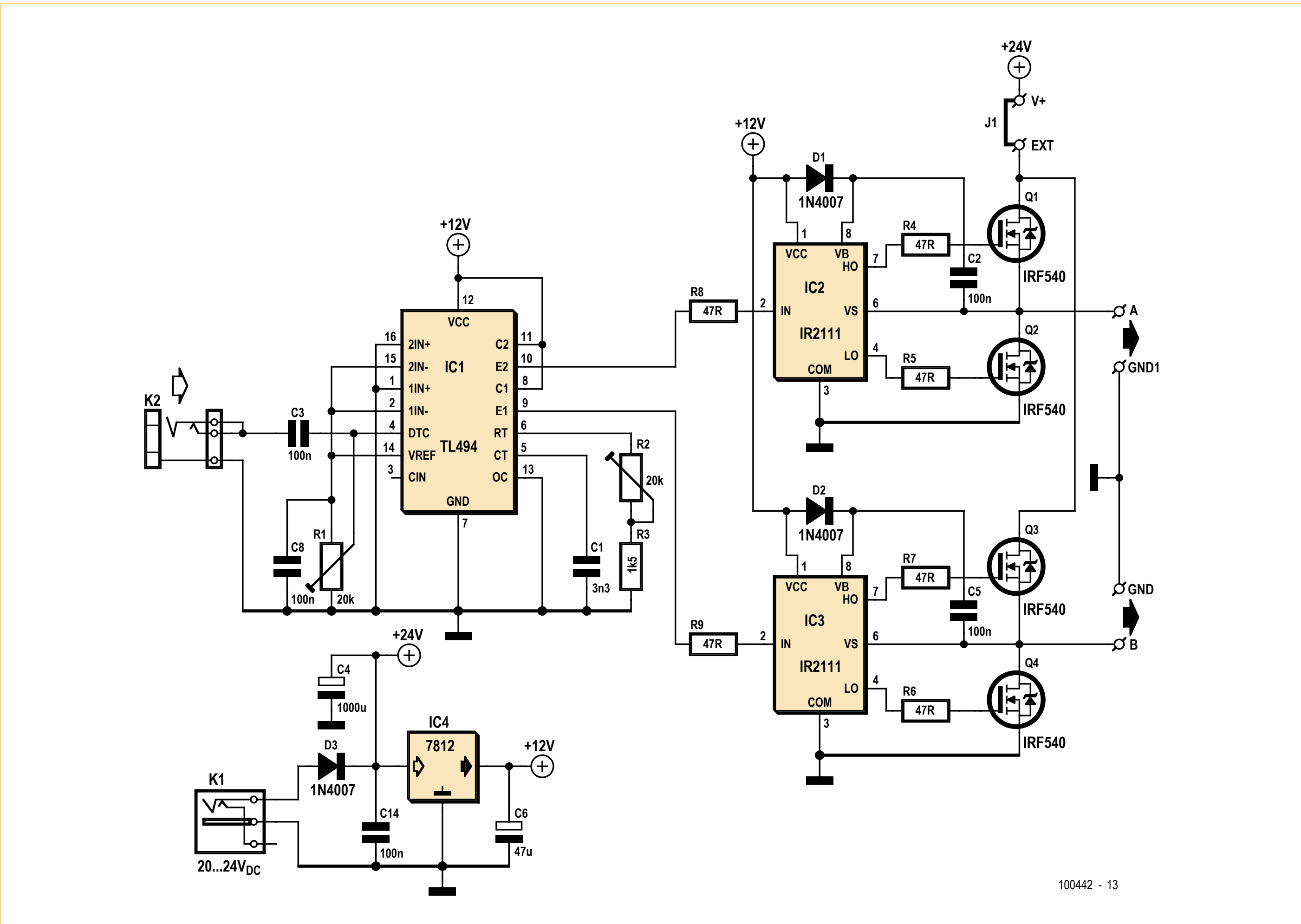

Figure 3. Circuit diagram of the PWM power driver for the ultrasonic parametric speaker unit. The audio input signal is connected to jack socket K2. Channel B is optional.

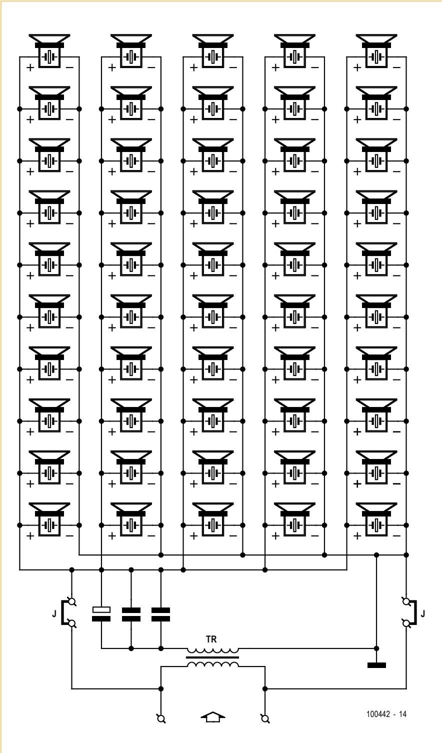

Figure 4. The ‘mini’ version of the directive loudspeaker consists of 50 ultrasonic piezo transducers connected in parallel and in phase. The step-up transformer and associated resonance caps are optional. The associated PWM driver in its basic form is suitable for up to 200 transducers.

Figure 5. A radio ferrite rod makes a good core for winding a 60-160 µH adjustable inductor that enables the largely capacitive transducers to be peaked at their resonant frequency (usually, 40 kHz).

setup.
The ‘non linear characteristic’ is due to the fact that it takes more time for air molecules to be restored to their original density than to be compressed (**Figure 2**). When the sound pressure is high, and frequency too, a shock wave may be produced by returning air molecules colliding with the ones being compressed. In fact, an audible sound is produced by any molecule not completely ‘returning’. When the frequency of the vibration rises, the ‘non-linear characteristic” tends to become noticeable by an effect best described as ‘air viscosity’.
There is another reason for the high directivity (i.e. small beamwidth) exhibited by a parametric speaker array. The supersonic wave is actually generated by a large number of small loudspeakers called transducers. The piezo-electric transducer is widely used both as a sensor and a transmitting device in car and home automatic systems. The directivity of the piezo transducer by itself is not too high. However, strength is in numbers, meaning the high directivity is due to many small transducers arranged in a plane-like shape. This is essential for making a truly directional speaker unit.

A parametric 2-channel speaker modulator

Double sideband modulation (DSB) is easily implemented using analogue switches. Frequency Modulation (FM) has the same effects basically if you look at the way supersonic sound waves compress air and interact.
The author first attempted a DSB modulator. The result: big sound, lots of distortion and the method might be suitable for a sound beam weapon. Next, a PWM system was built. Looking at the net result, PWM is very similar to FM. The audible sound obtained from PWM is weaker than from DSB, but of a better quality. A PWM modulator may be compared to a class-D amplifier without its low pass filter!
The schematic of a 2-channel PWM modulator is given in **Figure 3**. There are no special components. The TL494 PWM control circuit and the IR2111 half bridge MOSFET driver are used in their standard application circuits. The TL494 has an internal oscillator whose frequency is determined by trimpot R2 and capacitor C1. The basic pulsewidth is adjusted with R1. You need to set up optimum modulation with trimpots R1 and R2.
The audio input signal is connected to K2 (loudspeaker level required, not microphone or line). The board has two outputs, A and B, each driving an array of piezo transducers, optionally through an inductor (see below). Each channel is suitable for up to 200 transducers. The normal supply voltage is 20-24 DVC to K1. The FET stages may be powered by an external supply via the EXT terminal after removing wire link J1. Heatsinks may be required on the IRF540 FETs depending on the supply voltage and the transducers’ ratings (up to 60 VDC may be possible).
The U/S speaker schematic is large but unsurprising, see **Figure 4**. It represents one channel and a ‘mini’ version with just 50 transducers.

Speaker unit and optional coil

There are several type of ultrasonic transducer around. The author used 16 mm diameter devices specified for 40 kHz and 28 kHz. A minimum of 50 transducers is required to make an effective speaker unit. You need more than 100 transducers if you want to the unit to have any sort of range outdoors. All transducers should be carefully distributed to maintain phase. Remember, the wavelength is about 8 mm so a positioning error of 1 mm causes phase errors and loss of SPL.
Ultrasonic transducers are made from piezoelectric ceramic materials. When a voltage is applied to the device, a special type of foil is deformed inside, generating a supersonic sound wave of a specific frequency. Typically, the transducer’s sound output reaches 105–120 dB (at 30 cm distance) when a voltage of 10–20 V_{rms} is applied,

correspond-ing to 28–56 V_{pp} and that raises the question if a similarly high supply voltage is needed.

Electrically, an ultrasonic transducer has the properties of a capacitor, which can be made part of a series resonant circuit by putting an inductor in series. Tuning the inductor to about 40 kHz enables the transducer to be driven from a low supply voltage. A step-up transformer as shown in the speaker schematic is another way to get the transducers to operate at resonance.

The resonance frequency f_r may be calculated from

$$f_r = 1 / (2\pi \times L\,C)$$

Each ultrasonic transducer equals about 2,000–3000 pF worth of capacitance. Connecting 50 of them you get roughly 0.1–0.15 µF. To obtain resonance an inductance of about 60– 160 µH is called for, to connected between the driver's A and B outputs and the respective transducer arrays. Fine tuning is required to peak for resonance and the author produced an adjustable inductor from enamelled copper wire and a ferrite rod (**Figure 5**). For a 200-transducer version of the U/S speaker about 55 turns of wire gave best results (60-80 µH).

The ultrasonic transducers need to be checked individually to determine their polarity (phase). This may be done using an oscillator and a 2-channel oscilloscope as illustrated in **Figure 6**. One U/S device is connected to an oscillator (or generator) supplying a 40 kHz source signal that's also fed to one channel of the oscilloscope. The 'receiver' device gets connected to scope channel 2. Now you can view the signal and the timing at a glance (**Figure 7**).

Fun with the parametric speaker

It should be reiterated here that the project is experimental and intended to promote your own experiments. Connect the audio sound source through 3.5 mm jack socket K2, and connect the power supply to K1. You can probably hear a weak sound from the transducer array. Carefully adjust R1 and R2 for optimum sound quality. Check if the sound beam is anything like directive — it should be, even when using one channel (A or B). The author has tentatively indicated a range of about 50 meters (150 ft.) for a 200-transducer (!) system.

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Caution — Health Hazard.
Appropriate measures must be taken to prevent long term exposure to high ultrasonic sound levels.

[1] www.lradx.com

[2] www.holosonics.com

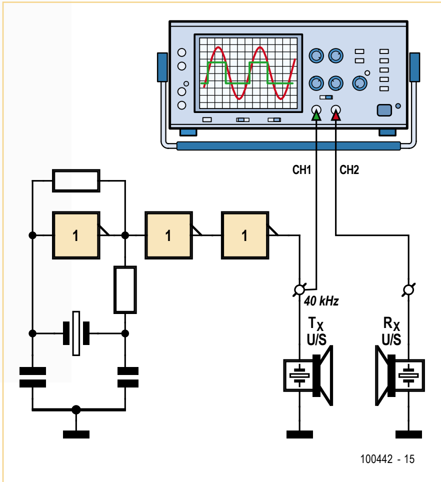

Figure 6. Test arrangement to establish the polarity of each and every piezo transducer used for the parametric array.

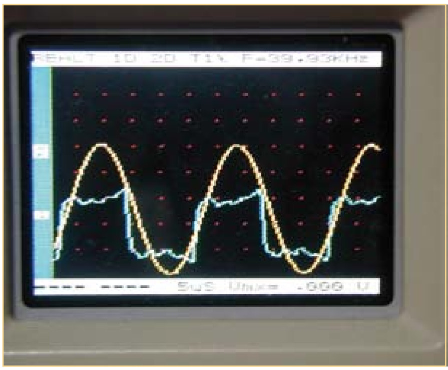

Figure 7. Scope image obtained with correct polarisation of the receiving U/S transducer.