Automatic resonant frequency matching of power amplifier by transformer loop sampling

Han Lim Lee, Hyeong-Seok Jang, Dong-Hoon Park, Moon-Que Lee✉ and Jong Won Yu

A new automatic resonant frequency matching technique based on voltage detection by sampling the output transformer loop of the radio-frequency power amplifier (PA) in ultrasonic medical applications is proposed. The proposed automatic resonant frequency matching circuitry is composed of a single-loop coil added to a PA output transformer, voltage divider, diode detector and micro-controller unit for frequency adjustment. Using the proposed circuitry, the resonant frequency shift due to output load variations can be effectively tracked and compensated to provide optimised power transfer to a non-linear load. For verification, a prototype ultrasonic medical application using a piezoelectric transducer is implemented and examined with silicone oil to check the resonance.

Introduction: Resonant frequency or load impedance variations are common phenomena in applications in which radio-frequency (RF) power sources are required such as wireless power transfer and high-power ultrasonic transducers [1, 2]. In ultrasound operations, using a transducer at its exact resonant frequency is critical in terms of highest power conversion. If an application is not matched to the resonant frequency of a transducer, the overall system performance is degraded by low-power efficiency and unstable vibration amplitude. To solve these problems, there have been several techniques to track the working frequency around the resonant frequency of ultrasonic transducers and the phase-locked loop (PLL)-based tracking system has been considered the most common method [3, 4]. However, the configuration with a PLL increases system complexity and exact calculations on phase difference must be conducted. Therefore, in this Letter, a simple automatic resonant frequency matching structure with a class-D power amplifier (PA) is proposed and verified with an ultrasonic transducer for medical applications.

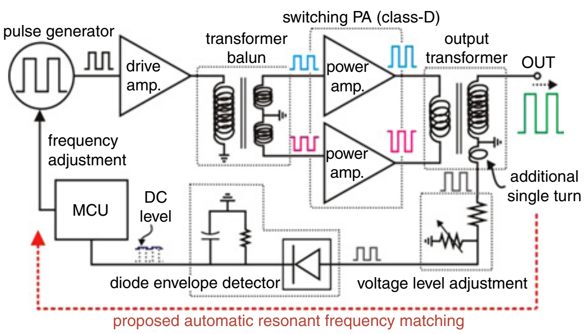

Fig. 1 *Structure of proposed automatic resonant frequency matching circuitry by searching minimum DC-level*

Design and analysis: Fig. 1 shows the proposed automatic resonant frequency matching structure configured with a drive amplifier and a class-D-type switching PA. The drive amplifier and transformer balun are used to drive the class-D PA for proper switching operation by turning on and off each transistor. Then, two PAs configured as a class-D PA are combined by the output transformer where an ultrasonic transducer is connected as well. However, the resonant frequency of the ultrasonic transducer varies during operation due to different loading conditions of the human body as shown in Fig. 2. To achieve stable vibration of a transducer with optimal power transfer, resonant frequency tracking and matching are necessary in medical applications. Thus, the proposed automatic resonant frequency matching circuitry adopts an additional single loop in an output transformer of the switching PA and controls the proper resonant frequency based on voltage detection from the sampling loop. If the transducer makes parallel resonance with the electrical system, the detected voltage becomes the maximum at the resonant frequency. Similarly, if the transducer makes series resonance with the electrical system, the detected voltage becomes the minimum at the resonant frequency. Since the proposed structure forms series resonance with the transducer, the resonant frequency can be found by finding the frequency at which the detected voltage is the minimum.

For high-power ultrasonic applications, which require a high supply voltage, the proposed output transformer loop sampling is the most effective way to detect the sampled voltage. As shown in Fig. 3, sensing resistors can be used at the drain or source of a switching transistor since the current flowing at the resonant frequency also varies. Fig. 3*a* shows that the sensing resistor is used with a differential amplifier at the drain side in order to detect the voltage variation around the resonant frequency. However, an operation amplifier with a common mode voltage rating that satisfies the supply voltage (~100 V) of high-power ultrasonic application is infeasible. Fig. 3*b* shows the use of a sensing resistor at the source side of the switching PA, but causing effects of degeneration and unstable switching operation.

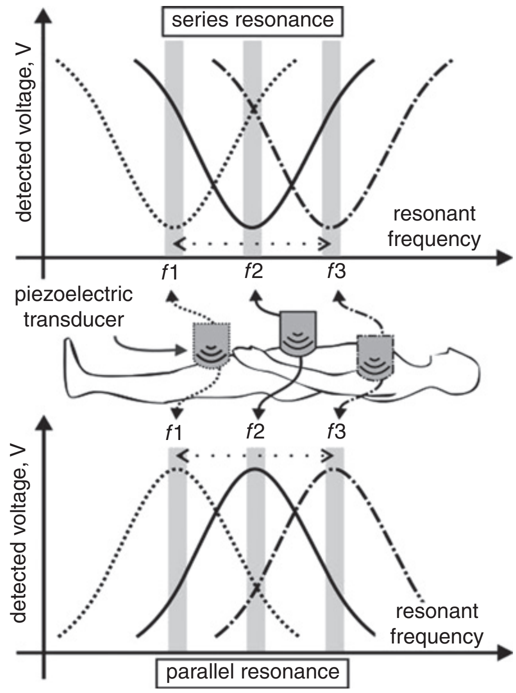

Fig. 2 *Variations in resonant frequency with respect to different contact points on human body*

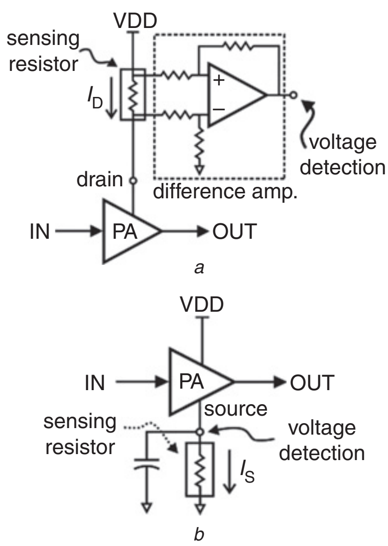

Fig. 3 *Voltage detection by sensing resistor to monitor resonance variations*
a Voltage detection at drain of switching PA
b Voltage detection at source of switching PA

Unlike the above-mentioned methods, the proposed structure adds a separate single-loop coil to the secondary coil side of the output transformer and thus does not affect the switching PA operation directly. That is, a high isolation between the sampling path and the switching

PA can be achieved while the additional single-loop samples the output voltage. Then, the sampled voltage is scaled down by the voltage divider to prevent excessive voltage from being fed to the micro-controller unit (MCU) and converted to the DC-level for MCU reading. Since the detected voltage should be the minimum at the resonant frequency, the proposed structure can find the resonant frequency and automatically adjusts the operation frequency to match the resonant frequency.

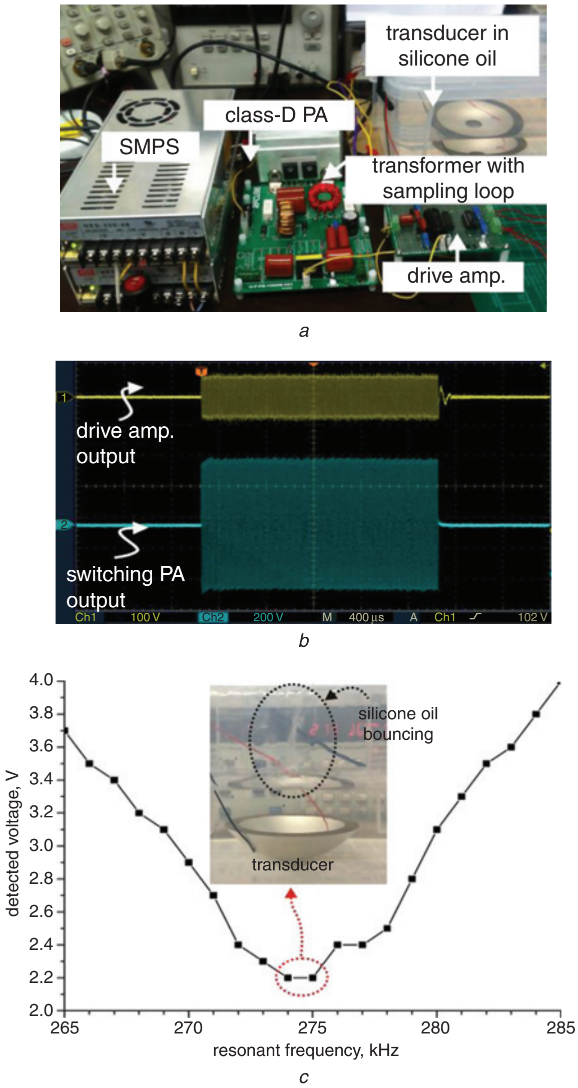

Fig. 4 *Implementation and measured results of proposed structure with ultrasonic transducer*

a Implementation of proposed structure
b Output voltages of drive amplifier and switching PA
c Detected voltage by sampling output transformer loop

Measurement results: For the verification of the proposed structure, a pulsed RF PA and automatic resonant frequency matching circuitry were implemented with a piezoelectric transducer that had a resonant frequency approximately between 250 and 300 kHz as shown in Fig. 4*a*. Here, the class-D RF PA was used because of its high efficiency and load variation insensitivity characteristics. Although the implemented prototype was targeted to the medical apparatus that can dissolve human body fat by ultrasound, it could not be examined with human body directly and thus silicone oil was used instead. The piezoelectric transducer was dipped in silicone oil so as to observe the droplet bouncing on the surface by the maximum vibration of the transducer at the resonant frequency. To find the exact resonant frequency, the proposed structure swept the operation frequency from 250 to 300 kHz through a commercially available ATMega controller. Using a 100 V supply voltage and an output transformer with about 1:2.2 turn ratio, Fig. 4*b* shows the measured output of the drive amplifier before the transformer balun was used and the output of the switching PA after the output transformer. The measured peak-to-peak output voltage delivered to the transducer was about 880 V. Finally, Fig. 4*c* shows the detected voltage with respect to the operation frequency. Having the additional sampling loop at the output transformer, the minimum voltage was detected as about 275 kHz and thus 275 kHz was found to be the resonant frequency of the transducer in silicone oil. At the resonant frequency, silicone oil bounced the most on the surface as shown in Fig. 4*c*.

Conclusion: A simple and effective automatic resonant frequency matching structure is proposed and has been verified through ultrasonic application at a frequency of <300 kHz. The proposed structure was configured with a pulsed switching PA in which an additional single-loop coil was used at the secondary coil side of the output transformer to sample the output voltage. On the basis of the voltage detection by the proposed structure, the resonant frequency of the piezoelectric transducer inside silicone oil was found to be 275 kHz and the maximum silicone oil bouncing was also observed at the adjusted resonant frequency.

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One or more of the Figures in this Letter are available in colour online.

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