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Novel Power MOSFET-Based Expander for High Frequency Ultrasound Systems

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Abstract

The function of an expander is to obstruct the noise signal transmitted by the pulser so that it does not pass into the transducer or receive electronics, where it can produce undesirable ring-down in an ultrasound imaging application. The most common type is a diode-based expander, which is essentially a simple diode-pair, is widely used in pulse-echo measurements and imaging applications because of its simple architecture. However, diode-based expanders may degrade the performance of ultrasonic transducers and electronic components on the receiving and transmitting sides of the ultrasound systems, respectively. Since they are non-linear devices, they cause excessive signal attenuation and noise at higher frequencies and voltages. In this paper, a new type of expander that utilizes power MOSFET components, which we call a power MOSFET-based expander, is introduced and evaluated for use in high frequency ultrasound imaging systems. The performance of a power MOSFET-based expander was evaluated relative to a diode-based expander by comparing the noise figure (NF), insertion loss (IL), total harmonic distortion (THD), response time (RT), electrical impedance (EI) and dynamic power consumption (DPC). The results showed that the power MOSFET-based expander provided better NF (0.76 dB), IL (-0.3 dB) and THD (-62.9 dB), and faster RT (82 ns) than did the diode-based expander (NF (2.6 dB), IL (-1.4 dB), THD (-56.0 dB) and RT (119 ns)) at 70 MHz. The -6 dB bandwidth and the peak-to-peak voltage of the echo signal received by the transducer using the power MOSFET-based expander improved by 17.4 % and 240 % compared to the diode-based expander, respectively. The new power MOSFET-based expander was shown to yield lower NF, IL and THD, faster RT and lower ring down than the diode-based expander at the expense of higher dynamic power consumption.

Keywords

Protection Devices; Expander; Power MOSFET; High Frequency Ultrasound System; Ultrasonic Transducers

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I. INTRODUCTION

High frequency (>15MHz) ultrasound imaging systems, which provide better axial and lateral resolution than systems at lower frequencies, have found applications for intravascular, skin and animal imaging [1, 2]. For such ultrasonic transducers and systems, the last stage of the transmitters (i.e. power amplifiers and pulsers) and the first stage of the receiver (i.e. preamplifiers and filters) may be separated by the transducer protection circuit [2]. Therefore, utilizing an expander will increase signal attenuation and electrical impedance mismatching between the components. These problems become more severe with high frequency ultrasound imaging systems [2]. Therefore, a better expander circuit design is to improve the performance of these systems.

A. Expander description

For high frequency imaging systems where two-way pulse-echo data is acquired to form an image, an expander circuit is typically used between the pulser and transducer. An expander allows HV pulse signals from the transmitter to pass through while suppressing the noise even when the transmitter is turned off. There are two expander schemes: passive and active type circuits, [3-7] which are shown in Fig. 1. Different passive and active type expander designs are described in order to elucidate their operating principle. The passive type expander has a diode pair configuration and the active type expander includes either a bridge diode or a high voltage (HV) switch.

The first type of active expander, the diode-bridge-based expander, [Fig. 1 (b)] is a diode bridge, which utilizes 4 bridge diodes. The internal current sources control the bias currents of these bridge diodes as shown in Fig. 1 (b). The power supplies (V_{dd} and V_{ss}) and control switch in turn determine these internal current sources. If the bias currents in the bridge diodes are the same, these diodes are shorted. Otherwise, the diodes are open [8].

The second type of active expander, the HV switch-based expander, [Fig. 1 (c)] works in a similar manner. This expander requires the use of level shifters and control logic circuits to determine the operation of the HV switches. The HV switch is a variable resistor that has a low impedance (ON) and high impedance (OFF) state. The control logic and level shifters control this impedance [9]. When the switch is turned on, the impedance is low and signals can pass through and when the switch is turned off no signals or noise can pass through.

B. Expander performance

Passive type expander circuits are widely used because of their simple structure. However, these expanders are not ideal because they generate excessive ring-down after high voltage excitation signals and also produce signal conduction loss [4].

Due to these undesirable effects, active type circuits such as diode-bridged-based and HV switches-based expander circuits have been developed [4-6]. The active type expander circuits reduce ring-down and minimize noise signals [4, 5]. Since the control logic circuits are capable of supporting rapid operation of the diode bridges and HV switches, it is possible to isolate the noise signals and ring-down after pulses are transmitted.

However, the active type expanders, especially the diode-bridge-based expanders, require the use of a high quality DC power supply due to poor noise rejection [10, 11]. Since the noise signal from the power supply is directly transmitted into the transducer, the performance of the transducer may be degraded. For the HV switched-based expanders, the insertion loss also depends on the internal resistances of the switches. The power consumption of the active type expander might be increased because there is static and dynamic power consumption due to use of the DC power supply. The comparison of the passive and active type expanders are summarized in the Table I.

II. ARCHITECTURE

In this paper, we only focus on passive type expander circuit because it is highly desirable to **minimize** the number of connections to the ultrasound array system. We propose here a passive type power MOSFET-based expander. This expander promises to provide **lower NF, IL** and **faster RT with lower ring-down** than the existing diode-based expander.

A. Expander architecture

The difference between the diode-based expander and the new expander design presented here is the use of several power MOSFETs. N-channel enhancement mode DMOS FETs (double-diffusion metal oxide semiconductor field effect transistors) were used as the elements of the new expander design. These power MOSFETs are used in other power applications and are useful components in an expander because they sustain HV signals and have fast-switching times. The architectures of the power MOSFET-based and diode-based expander are shown in Fig. 2. The power MOSFET has a high breakdown voltage and low on-state resistances and capacitances, giving it low signal loss and a fast switching time. As compared with a single N-channel MOSFET, when they are positioned in series, the total drain-source on-state resistance, or on-resistance, is increased but the total junction capacitance is decreased. Moreover, with the MOSFETs' parallel configuration, their on-resistance would also be decreased but the junction capacitance would be increased. However, both the series and parallel MOSFET configurations could improve the power-handling capability over a single power MOSFET and does not diminish the switching speed of the expander.

As shown in Fig. 2 (b), one diode pair in a diode-based expander could reduce the original input signal by $0.7 \sim 1 V_{p-p}$. To block the noise from the pulser, two-stage diode pairs are typically used in diode-based expanders. Using two-stage diode pairs instead of a single pair will necessarily increase the signal conduction loss to $1.4 \sim 2 V_{p-p}$ and increase the THD of the expander. Moreover, the voltage reductions of the diode-based expander may become more severe depending on the test conditions. Conversely, the power MOSFET-based expander can reduce signal conduction loss at higher voltages because its transistor has a low internal resistance so it can pass HV signals with less loss. The transistor also has higher threshold voltage than the built-in body diodes which allow it to attenuate higher levels of noise than the diodes can. This characteristic of power MOSFETs has been previously described in the literature [12, 13].

B. Power MOSFET-based expander operation

As shown in Fig. 3 below, the positive and negative HV signals from a pulser can flow through the upper and lower sides of the expander, respectively, so that the signal conduction loss is minimized because of low internal resistances of the power MOSFETs. The returned or discharged current from the ultrasonic transducer can flow through the built-in body diodes of the Power MOSFET because the diode-forward voltage of the built-in body diode is usually lower than turn-on gate threshold voltage of the power MOSFET [7, 12]. Therefore, the return signal from the ultrasonic transducer will have less effect on the pulser because of the two different paths available. The power MOSFET-based expander also yields lower signal reduction and more isolation than the diode-based expander because of the built-in diodes.

III. DESCRIPTION OF THE POWER MOSFET-BASED EXPANDER

To construct the expander, power MOSFET devices must be properly selected because the pulser can affect the performance of the transducers and the expander is directly attached to the output load of the pulser. **In order to properly select the devices**, an analysis of the equivalent circuit model of power MOSFETs [14-16] needs to be studied since it can be used to predict the behavior of the expander.

A. The equivalent circuit model of a power MOSFET

The equivalent circuit model of a power MOSFET device is shown in Fig. 4 (a). At higher voltage operation of the power MOSFET, the drain-source on-state resistance (R_{DSN}) of the transistor must be minimized because the voltage drop of the expander needs to be minimized. And, the internal input capacitances (C_{GSN} and C_{GDN}) of the transistor needs to be lower because the input resistance (usually 50–75 Ω) of the devices and the input parasitic capacitances of the transistor can limit the allowable pulse width of the input signal of the expander [17]. The output capacitance (C_{DSN} and C_{DDN}) and the Miller capacitance (C_{GDN}) of the devices normally affect its response time so their values also need to be optimized at the certain level of voltages [15]. However, the power MOSFET-based expander described here has used a gate-drain coupling MOSFET. As a result, the input/output capacitances and output resistances need to be considered as shown in Fig. 4 (b).

B. The equivalent circuit model of the power MOSFET-based expander

In order to estimate the performance of the expander under HV operation, the large signal model of the power MOSFET was studied as shown in Fig. 5. The signal loss of the gate-drain-coupling power MOSFET is mainly dependent on the drain-source on-state resistance (R_{DSN}), the forward transconductance (g_{fsn}) and the input & output capacitances (C_{GSN} , C_{DSN} and C_{DDN}). Expressions for the forward transconductance and the drain-source on-state resistance (g_{fsn} and R_{DSN}) are given here [16]

$$R_{DSN} = \frac{(V_{GSN} - V_{THN})}{\beta_n} \quad g_{fsn} = \beta_n (V_{GSN} - V_{THN}) \quad (1)$$

where β_n is the intrinsic transconductance, V_{GSN} is the gate-source voltage, and V_{THN} is the threshold voltage of the N-channel power MOSFET.

Eq. (1) shows that the drain-source resistance (R_{DSN}) can be increased as the applied voltage to the gate-source (V_{GSN}) is increased. However, the intrinsic transconductance (β_n) parameter is saturated at a certain voltage due to electron surface mobility (μ) [17-20]. Therefore, the drain-source resistances of the power MOSFET devices may become saturated as the applied voltage is increased [17]. The transconductance value (g_{fsn}) ideally would go down as the applied voltage is increased [19, 20]. However, the input and output capacitances (C_{GSN} , C_{DSN} and C_{DDN}) would usually dramatically decrease and become saturated as the applied voltage is increased [20-23]. Therefore, we can safely conclude that the lower parasitic resistances (R_{DSN}) and capacitances (C_{GSN} , C_{DSN} and C_{DDN}) at certain voltages need to be selected.

As shown in Fig. 5 (c) and (d), the IL from the expander can be estimated from the equivalent circuit model of the expander. Therefore, the IL depends on the total parasitic resistances (R_{MN}) and capacitances (C_{MN}) at a certain voltage. In order to predict the IL or magnitude vs. frequency responses, -3 dB bandwidth of the power MOSFET was also derived from the equivalent circuit model of the drain-gate-coupling power MOSFET in Fig. 5 (a)-(b).

$$f_{-3dB, Power \text{ MOSFET}} = \left[2\pi \cdot \frac{(C_{DdN} + C_{DSN} + C_{GSN})}{1 + 1/(R_{DSN} + g_{fsn}^{-1})} \right]^{-1} \quad (2)$$

where C_{DdN} is the parasitic diode capacitance, C_{DSN} is the parasitic drain-source capacitance and C_{GSN} is the parasitic gate-source capacitance of a power MOSFET.

The -3 dB bandwidth of a power MOSFET depends on the parasitic capacitances (C_{GSN} , C_{DSN} and C_{DDN}) and resistances (R_{DSN} and g_{fsn}^{-1}) at a certain voltage level. Using the equivalent circuit as shown in Fig. 5 (c), the -3 dB bandwidth of the expander ($f_{-3dB, expander}$) could be derived, similar to Eq. (2). The datasheet of the manufacturer is not sufficient to be used for -3 dB bandwidth calculation so the Cadence circuit program (Cadence Design Systems, San Jose, CA, USA) was used to obtain the parasitic impedances of the power MOSFET. The calculated -3 dB bandwidth of the expander using Eq. (2) was 1.52 GHz and the measured -3 dB bandwidth, as measured by a network analyzer (N5230A PNA-L, Agilent Technologies, Santa Clara, CA, USA) was 1.36 GHz. The measured -3 dB bandwidth of the expander device was smaller than the simulated value because the line traces of the PCB board and BNC connector also affect the performances of the expander at very high frequency (> 1 GHz) operation. However, the bandwidth of power MOSFET would not severely limit the input signal of the pulser.

IV. EXPERIMENTAL METHODS

The power MOSFET-based expander using DMOS FET (BSS123, Diodes Inc, Plano, Texas, USA) and the diode-based expander using diodes (PMBD 7000, NXP Semiconductors, Eindhoven, Netherlands) have been implemented on a printed circuit board

to minimize attenuations from the devices' interconnection. The experimental methods to evaluate the performances of the expanders are described below.

A. Noise figure

In the pulse-echo response, the pulser may send the noise signals to the receiver. Therefore, the function of the expander is to suppress the noise signals from the pulser [24]. Since NF is a parameter to measure how much the noise of the devices deteriorate the performances of the system [25], the NF of the expanders needs to be measured in order to evaluate their noise blocking performance.

The noise figure measurement was performed with a spectrum analyzer (E4401B ESA-E Agilent Technologies, Santa Clara, CA), function generator (AFG2020, Tektronix, Beaverton, OR, USA) and a high gain RF power amplifier (325LA, Electronics & Innovation, Rochester, NY, USA). The "Gain Method" was used to measure the noise figure since it is proven to be very accurate [26] if the device- under-test (DUT) has a very high gain. The diagram of the noise figure measurement is shown in Fig.6. The noise figure of the device (NF) [26] can be represented as

$$NF = P_{N_{outD}} + 174 \text{ dBm/Hz} - \text{Gain} \quad (3)$$

where $P_{N_{outD}}$ is the output noise density and Gain is the gain of the devices.

The noise figure of multi-stage devices (NF_{total}) is as follows [25]

$$NF_{total} = NF_1 + \frac{NF_2 - 1}{A_{v1}} + \dots + \frac{NF_n - 1}{A_{v1}A_{v2} \dots A_{vn}} \quad (4)$$

where NF_1 , NF_2 and NF_n are the first, second and n-th stage noise figure, and A_{v1} , A_{v2} , A_{vn} are the first, second and n-th stage gain of the device.

Therefore, the noise figure of the expander device (NF_{exp}) can be calculated as

$$NF_{exp} = [NF_{amp+exp} - NF_{amp}] \cdot A_{v,amp} + 1 \quad (5)$$

where $NF_{amp+exp}$ is the cascade NF of the RF power amplifier and expander, NF_{amp} is the NF of the amplifier and $A_{v,amp}$ is the gain of the RF power amplifier.

Since we could obtain the output noise density ($P_{N_{outD}}$) using Eq. (3), it was possible to calculate the cascade NF ($NF_{amp+exp}$) of the power amplifier and expander. The NF of the expander was then calculated using Eq. (5).

B. Insertion loss

To measure the IL or THD of the expanders, a continuous sine wave from a function generator was sent to the RF power amplifier and the output signals of the power amplifier drove the expander, which in turn was sent through a power attenuator to the oscilloscope (LC-534, LeCroy, Chesnutt Ridge, NY, USA). The magnitudes of the signals were then recorded using an oscilloscope with a 50 Ω load setting. The IL was obtained by dividing the

magnitude of the output signal of the expander by its original magnitude without an expander.

C. Total harmonic distortion

Diodes and MOSFET devices are non-linear devices and consequently produce several harmonic signals. Therefore, a total harmonic analysis of the devices needs to be carried out to evaluate their nonlinear characteristics [27]. The THD of the expanders can be calculated as

$$THD = \frac{(V_2)^2 + (V_3)^2 \dots + (V_n)^2}{V_1^2} \quad (6)$$

where V_1 , V_2 , V_3 and V_n are the amplitude of the fundamental, 2nd, 3rd, nth harmonic signals of the devices, respectively.

A single-tone sine wave signal from the function generator was amplified through the RF power amplifier and the output signal was sent to the expander. Subsequently, the magnitude of the signals was recorded in the oscilloscope using a LabVIEW program (LabVIEW, National Instruments, Austin, TX, USA) and the Fast Fourier Transform (FFT) of the harmonic signals of the expander was plotted and the THD was calculated using Eq. (6). The effective bit resolution and sampling frequency of the oscilloscope are 6 bit and 1GS/s respectively. The five numbers of the harmonics was chosen due to the limitations in sampling frequency of the oscilloscope.

D. Response time

Since the RT of the protection devices can affect transducer's ring-down in the pulse-echo measurement [3], [18], the transient responses of the expander needs to be addressed. The RT was the time elapsed from when the input signal starts to when the output signals reaches $\pm 1\%$ point of the final output voltage.

In order to use the expander for high frequency ultrasound systems, the rise/fall time of the expander must be considered because the transient performance of these systems depends on the rise/fall time of the transmitted pulse [28]. The rise time is defined as the time that it takes for the output pulse to rise from 10 % to 90 % of final output value and the fall time is the time for the pulse to fall from 90 % to 10 % of the final output value [29].

While fast rise/fall times are desirable, systems with short RT values may have transmit pulse overshoot or undershoot, which will degrade system performance [30]. Therefore, the overshoot and undershoot voltages must also be measured. The overshoot voltage is defined as the maximum excursive voltage in response to the increasing output current during the rise time for a positive pulse or the decreasing output current for a negative pulse [31]. The undershoot voltage is defined as maximum excursive voltage in response to the decreasing output current during the fall time for a positive pulse or the increasing output current during the rise time for a negative pulse [31]. The percentage values of the overshoot and undershoot voltage were calculated by dividing the measured voltage by the amplitude of the output voltage of the expander [29]. The undershoot voltage for positive pulses at rise

time, and overshoot and undershoot voltages for negative pulses at the rise time were too small to be measured.

To measure this capability, a positive or negative pulse waveform from a function generator was sent to the RF power amplifier and then to the expander, whose output signal was measured by the oscilloscope with a $50\ \Omega$ load and power attenuator. Then the RT with rise/fall time and overshoot/undershoot voltage of the suppressed waveform was measured. The block diagram of measurement setup for IL, THD and RT is schematically illustrated in Fig. 7 (a).

E. Electrical impedance

To evaluate the impedance mismatching between the expander and transducer, the electrical impedance of the expander was measured using an impedance analyzer (HP 4294A, Agilent Technologies, Santa Clara, CA, USA). The output signals of the amplifier were sent through the expander to the transducer, which characteristically has an impedance of $50\ \Omega$.

Therefore, a 50 ohm load was attached to the expander when measuring its electrical impedance to simulate the effect of the transducer during operation. The experimental diagram for the measurement is shown in Fig. 7 (b).

F. Pulse-echo measurement

The pulse-echo measurement of the transducer was performed in order to further evaluate the capability of the expanders. A single-element 70 MHz LiNbO_3 piston transducer with 1.3 mm aperture size and 2 mm focal distance was placed in a de-ionized water tank facing a quartz target 2mm away. Each expander was connected to the transducer and limiter and the preamplifier was also connected to the oscilloscope using 50 cm coaxial cables. Using a pulser (AVB2-TB-C, Avtech Electrosystems, Ottawa, Ontario, Canada), a 70 MHz pulse with 200 Hz pulse repetition frequency and 0.1 μs delay was used to trigger the transducer. The return echo waveform received by the transducer passed through a diode limiter (DL-1, Matec Instruments, Northborough, MA, USA) followed by a 36 dB gain preamplifier (AU-1114, MITEQ, Hauppauge, NY, USA). The waveforms were recorded using a LabVIEW program where the FFT frequency response of the echo was calculated. The experimental diagram for the pulse-echo response is schematically illustrated in Fig. 8.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The NF, IL, THD, RT, EI and DPC as well as the pulse-echo response were measured. The performance of the power MOSFET-based expander and diode-based expander will then be compared. The simulation data of the IL and THD of the expanders were also provided to estimate their performance. However, other simulation data such as RT, EI, DPC and pulse-echo response was not discussed in the paper because there are no available manufacturer library models for commercial pulsers, preamplifiers and limiters.

High frequency ($> 15\ \text{MHz}$) transducers usually have lower sensitivity than low frequency transducers. Therefore, high frequency transducers should be excited by higher voltage signals than $10\ \text{V}_{\text{p-p}}$ through the expanders in order to achieve sufficient sensitivity of the transducer, meaning it is more than the minimum detection sensitivity ($> 5\ \text{mV}$) of the

oscilloscope. Therefore, the output test voltages of the power amplifier were selected to be more than 10 V_{p-p} for the experimental measurement.

A. Noise figure

Using the “Gain Method” [26], the noise figures of the expanders were measured. The measured NF of the power MOSFET-based and diode-based expander was 0.76 and 2.6 dB at 70 MHz, respectively. As shown in Fig. 9, the measured NF of the power MOSFET-based expander was substantially lower than that of the diode-based expander. These results indicate that the power MOSFET-based expander has better noise blocking capability.

B. Insertion loss

The IL of the power MOSFET-based and diode-based expander was obtained with PSpice, a circuit design software program (Cadence Design Systems, San Jose, CA, USA). With a 70 MHz 50 V_{p-p} continuous sine wave input, the expected IL of the power MOSFET-based and diode-based expander was -0.28 and -0.71 dB, respectively. The measured minimum voltage of the RF power amplifier driven by the function generator without an attenuator was approximately 16 V_{p-p} at 1 MHz. The maximum voltage of the drain-source and drain-gate of the DMOS FET (BSS123) is 100 V. The repetitive peak reverse voltage (V_{RRM}) and the reverse voltage (V_R) of the diode (PMBD 7000) are also 100 V. Therefore, to predict the behavior of the expanders we tested each using two sets of inputs. In the first set of inputs the signal amplitude was fixed at 50 V_{p-p} and frequency was tested every 10 MHz from 10 to 100 MHz. In the second set of inputs the signal frequency was fixed at 70 MHz and the signal amplitude was tested every 10 V_{p-p} from 20 to 90 V_{p-p}. Fig. 10 (a) and (b) show that for either IL vs. frequency or IL vs. voltage, the IL of the diode-based expander was usually 1 to 1.5 dB worse than that of the power MOSFET-based expander. This is because the internal structure of power MOSFET-based expander is designed to reduce IL.

C. Total harmonic distortion

Using PSpice simulation, a 70 MHz 50V_{p-p} continuous sine wave was applied and the 1st – 5th harmonic was included to calculate the THD. The expected THD of the power MOSFET-based and diode-based expander was -68.2 and -59.4 dB, respectively. Fig. 11 (a) shows that as frequency increases past 20 MHz, the THD of the power MOSFET-based expander is better than that of the diode-based expander. At 70 MHz, the power MOSFET-based expander yields a lower THD (-62.9 dB) than the diode-based expander (-56.0 dB). Fig. 11 (b) shows that the THD of the power MOSFET-based expander was better than that of diode-based expander across all input voltages. These results show that the power MOSFET-based expander is less affected by higher frequencies and higher voltages than the diode-based expander due to lower non-linear harmonic effect of the individual power MOSFET devices within the expander.

D. Response time

To measure the response time of the expander, a 70 MHz pulse signal from a function generator, which had minimum rise and fall time of 3 ns, was used to drive the RF power amplifier. Next, the output signals from the amplifier were sent through the expander and

attenuator. Finally, the final output waveforms were displayed on an oscilloscope with a 50 Ω load setting. When the final output voltage after the power amplifier was applied to the expanders, the RT of the positive output voltage of the power MOSFET-based and diode-based expanders was found to be 65 and 106 ns, respectively as shown in Fig. 12 (a). Fig. 12 (b) shows that the RT of the negative output voltage of the power MOSFET-based and diode-based expander was 82 and 119 ns, respectively. The power MOSFET-based expander shows a faster reverse recovery time (82 ns) than the diode-based expander (119 ns) as shown in Fig. 12 (b).

The measured rise time and fall time of the power MOSFET-based and diode-based expander were both 3 ns, which is fast enough to be used for high frequency ultrasound systems [32, 33]. Since voltage overshoots/undershoots are equally undesirable, the greater value was recorded as the 'maximum' overshoot/undershoot. The maximum overshoot/undershoot of the power MOSFET-based and diode-based expander was 7.5 V_{p-p} (13%) and 15.9 V_{p-p} (29.7%), respectively. This experimental data shows that the power MOSFET-based expander has a faster response with less ring-down than the diode-based expander, which is critical in lowering spatial inference and improving image resolution of an imaging system. The measured overshoot and undershoot voltages for positive and negative output pulses of the expanders are summarized in Table III.

E. Electrical impedance

The electrical impedance of the expander was measured with a 50 Ω load attached to simulate the loading effect of a transducer. In Fig. 13, the electrical impedance vs. frequency of the expander was plotted. Fig. 13 (a) shows that the impedance magnitude of the power MOSFET-based and diode-based expander was 66.4 Ω and 337.6 Ω at 70 MHz, respectively. The result shows that the measured magnitude of the power MOSFET-based expander was lower than that of diode-based expander. Fig. 13 (b) also shows that the phase of the power MOSFET-based and diode-based expander was -25.39 $^\circ$ and -88.83 $^\circ$ at 70 MHz. The phase of the power MOSFET-based expander was also lower than that of the diode-based expander. Therefore, the loading of the power MOSFET-based expander has less influence on the transducer than that of the diode-based expander. Better impedance matching with the transducer can increase its sensitivity.

F. Dynamic power consumption

Compared to active type expander devices, the passive type expander devices such as power MOSFET-based and diode-based expanders do not require bias control signals to function. We measured and compared the dynamic power consumption of both expanders. The dynamic power consumption (P_{Dyn}) can be calculated using Eq. (7):

$$P_{Dyn} = f_{pulse} t_{pulse} \frac{V_{pulse}^2}{R_{device}} \quad (7)$$

where f_{pulse} , t_{pulse} and V_{pulse} are the pulse repetition frequency, pulse duration and pulse amplitude, respectively and R_{device} is the resistor of the device.

An estimate of the dynamic power consumption of the power MOSFET-based and diode-based expanders by a pulser was calculated using Eq. (7) and their values were found to be 1 and 0.2 mW, respectively. The power MOSFET-based expander inevitably consumes more power than the diode-based expander because the power MOSFET device has relatively high current at same voltage level compared with the diode [20].

G. The pulse-echo responses

The results of the pulse-echo measurement are shown in Fig. 14. It shows that the -6 dB bandwidth and the peak-to-peak voltage of the transducer using power MOSFET-based expander was 17.4 % wider and 240 % greater ($1.05 V_{p-p}$), respectively, than those of the diode-based expander. This demonstrates that using the power MOSFET-based expander rather than the diode-based expander improves transducer sensitivity and bandwidth since the measured IL of the power MOSFET-based expander was lower than that of the diode-based expander and the impedance of the power MOSFET-based expander was closer to 50 Ω than that of the diode-based expander, which reduces signal loss through impedance mismatching. In order to further improve the bandwidth and sensitivity of the transducer, the combined impedances of the adjacent electronics such as pulser, expander, preamplifier and limiter circuit needs to be as close to 50 Ω as possible over the bandwidth of the transducer. Impedance matching is critical to improve the performance of the high frequency transducers [24].

H. Commercial implementation considerations

In any system, performance needs to be evaluated in the context of cost and ease of implementation. A power MOSFET (\$0.1) is more expensive than a diode (\$0.01) and more space is needed for the ultrasound array system to implement power MOSFET expanders due to their larger footprint. Therefore, HV ASIC may be the only solution implementation in commercial systems. Besides drastically reducing the expander's footprint, using an ASIC process would also help reduce undesired parasitic capacitances from the MOSFETs' interconnections. In order to utilize a HV ASIC process, ESD (Electro Static Discharge) diodes would have to be included so the parasitic capacitances of the ESD diodes are optimized to reduce interference with the power MOSFETs [34, 35]. The specific on-resistance (R_{sp}) of a power MOSFET also needs to be considered because this parameter determines the on-state drain-source resistance (R_{DS}) and breakdown voltage of the power MOSFET [34]. For the power MOSFET, the forward voltage of the built-in protection diodes (V_{SD}) should be higher than threshold voltage of the transistor in the power MOSFET (V_{TH}) to minimize the interaction between the transducer and pulser. The drain-source on-state resistance (R_{DS}) at high drain-source voltages (V_{DS}) should be minimized to reduce conduction loss and decrease RT. Furthermore, in the linear region of the power MOSFET, the operating voltage range of the drain-source (V_{DS}) and drain-gate (V_{GS}) of the MOSFET needs to be maximized to reduce the signal distortion from the pulser. Additionally, the on-state resistance (R_{DS}) must tolerate transmit current limit of the pulser. Moreover, input and output capacitances (C_{iss} and C_{oss}) must be optimized at higher frequencies and voltage levels to achieve a faster RT and wider bandwidth for the system.

VI. CONCLUSION

This paper presents a power MOSFET-based expander for high frequency ultrasound imaging systems. At 70 MHz with a 50 V_{p-p} continuous sine wave signal as the input, the power MOSFET-based expander performed better than the diode-based expander with respect to NF (0.76 dB), IL (−0.3 dB) and THD (−62.9 dB) as shown in table V. It also demonstrated a faster reverse recovery time (82 ns) with lower ring-down at 70 MHz with a 70 V_{p-p} negative pulse as the input. The power MOSFET-based expander was tested with a single element 70 MHz ultrasonic transducer. The −6 dB bandwidth of echo signal improved by 17.4 % and peak-to-peak voltage increased by 240 % relative to the diode-based expander. However, the power MOSFET-based expander consumed more power (1 mW) than the diode-based expander (0.2 mW) at 70 MHz. For high frequency ultrasound applications that require **lower signal attenuation** and **THD** as well as **faster RT with lower ring-down**, this power MOSFET-based expander is a viable alternative.

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Highlights

For the pulse-echo measurement, the -6 dB bandwidth and the peak-to-peak voltage of the echo signal received by a 70 MHz transducer using the power MOSFET-based expander (a new type of expander that utilizes power MOSFET components) improved by 17.4 % and 240 % compared to the diode-based expander which is essentially a simple diode-pair, respectively. These results showed that higher sensitivity could be achieved with a power MOSFET-based expander. For high frequency ultrasound applications that require lower signal attenuation and total harmonic distortion as well as faster recovery time with lower ring down, the power MOSFET-based expander is a viable alternative.

Fig. 1.
The architecture of the expanders. (a) diode-based expander, (b) diode-bridge expander and (c) HV switch-based expander.

Fig. 2.
The schematic diagrams of (a) power MOSFET-based and (b) diode-based expanders.

Fig. 3.

The current flow diagrams of the power MOSFET-based expander. (a) HV positive and negative signals from the pulser and (b) low voltage return positive and negative signals from the transducer.

Fig. 4.

(a) The equivalent circuit model of a power MOSFET and (b) equivalent circuit model of a gate-drain-coupling power MOSFET.

Fig. 5.

(a) A drain-gate-coupling power MOSFET, (b) the equivalent circuit of the drain-gate-coupling power MOSFET, (c) the equivalent circuit of a power MOSFET-based expander and (d) the current model of a power MOSFET-based expander.

Fig. 6.
Noise figure measurement setup for the expander devices.

Fig. 7.

(a) The experimental diagram for the measurement of the IL, THD and RT and (b) for the EI measurement of the expanders.

Fig. 8.
The schematic diagram for the pulse-echo measurement with a transducer.

Fig. 9.
The NF of the expanders.

Fig. 10.

The IL of the expander (a) when 50 V_{p-p} sine wave test signal at different frequencies (10 MHz to 100 MHz) were applied and (b) when 70 MHz sine wave test signal at different input voltages (20 V_{p-p} to 90 V_{p-p}) were applied.

Fig. 11.

The THD of the expanders (a) when 50V_{p-p} sine wave test signal at different frequencies (10 MHz to 100 MHz) were applied (b) when 70MHz sine wave at different input voltages were applied (20 V_{p-p} to 90 V_{p-p}).

Fig. 12.

The transient responses of the output voltages after expanders when 70 MHz V_{p-p} positive and negative pulses were applied; (a) the response time with rise and fall time for positive pulse signals, (b) the response time with rise and fall time for negative pulse signals, (c) the overshoot and undershoot voltages for positive pulse signals and (d) the overshoot and undershoot voltages for negative pulse signals.

Fig. 13.

The electrical impedances of the expanders; (a) the magnitude of the electrical impedance of the expanders and (b) the phase of the electrical impedance of the expanders.

Fig. 14.
The pulse-echo responses of a transducer with the expanders.

Table I

The characteristics of the passive and active type expanders.

	Passive	Active
Advantages	Simple	Lower ring down and NF
Disadvantages	Excessive ring down and higher IL	Requires control circuit and high quality power supply

TABLE II

The RT of the positive and negative HV pulses after the expanders

	Positive HV pulses [ns]	Negative HV pulses [ns]
Diode-based expander	106	119
Power MOSFET-based expander	55	82

TABLE III

The overshoot and undershoot voltages caused by HV positive and negative pulses

	Positive HV pulses [V_{p-p} (%)]			
	Rise	Rise	Fall	Fall
	OS	US	OS	US
Diode-based expander	2.5 (5.2%)	----	12.6 (26.2%)	7 (14.5%)
Power MOSFET-based expander	2.5 (4.3%)	----	7.5 (13%)	6.9 (12%)

	Negative HV pulses [V_{p-p} (%)]			
	Rise	Rise	Rise	Fall
	OS	US	OS	US
Diode-based expander	----	----	15.9 (29.7%)	6.3 (11.7%)
Power MOSFET-based expander	----	----	6.5 (10.2%)	5.0 (7.8%)

TABLE IV

The input parameters of dynamic power consumption

	f_{pulse}	t_{pulse}	V_{pulse}	R_{device}
Diode-based expander	1 kHz	14.3 ns	70 V	337 Ω
Power MOSFET-based expander	1 kHz	14.3 ns	70 V	64 Ω

TABLE V

Summary of the measured performances of the expanders

Parameters	Diode-based expander	Power MOSFET-based expander
Noise figure (dB)	2.6	0.76
Insertion loss (dB)	-1.4	-0.3
Total harmonic distortion (dB)	-56.0	-62.9
Reverse recovery time (ns)	119	82
Rise/fall time for $\pm$ HV pulses (ns)	3	3
Dynamic power consumption (mW)	0.2	1
Electrical impedance (Ω)	357.6	66.4