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Author Manuscript
*J Med Syst*. Author manuscript; available in PMC 2015 April 01.

Published in final edited form as:
*J Med Syst*. 2014 April ; 38(4): 34. doi:10.1007/s10916-014-0034-0.

# Protection Circuits for Very High Frequency Ultrasound Systems

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## Abstract

The purpose of protection circuits in ultrasound applications is to block noise signals from the transmitter from reaching the transducer and also to prevent unwanted high voltage signals from reaching the receiver. The protection circuit using a resistor and diode pair is widely used due to its simple architecture, however, it may not be suitable for very high frequency (VHF) ultrasound transducer applications (>100 MHz) because of its limited bandwidth. Therefore, a protection circuit using MOSFET devices with unique structure is proposed in this paper. The performance of the designed protection circuit was compared with that of other traditional protection schemes. The performance characteristics measured were the insertion loss (IL), total harmonic distortion (THD) and transient response time (TRT). The new protection scheme offers the lowest IL (−1.0 dB), THD (−69.8 dB) and TRT (78 ns) at 120 MHz. The pulse-echo response using a 120 MHz $LiNbO_3$ transducer with each protection circuit was measured to validate the feasibility of the protection circuits in VHF ultrasound applications. The sensitivity and bandwidth of the transducer using the new protection circuit improved by 252.1 and 50.9 %, respectively with respect to the protection circuit using a resistor and diode pair. These results demonstrated that the new protection circuit design minimizes the IL, THD and TRT for VHF ultrasound transducer applications.

### Keywords

Very high frequency; Ultrasonic transducers; Protection circuits; MOSFET

## Introduction

VHF ultrasound has recently been highlighted in a number of biomedical applications including acoustic microscopy, acoustic radiation force imaging, cellular stimulation and micro-particle manipulation [1, 2]. However, the VHF transducers typically have much lower sensitivity and bandwidth than low-frequency transducers because the miniature size of the high frequency transducer aperture reduces the maximum tolerable power that drives these devices [3]. Additionally, the parasitic impedances of the ultrasound systems as well as



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This article is part of the Topical Collection on *Systems-Level Quality Improvement* cable loading critically affect the transducers' sensitivity and bandwidth [3]. In order to achieve suitable signal quality for the VHF transducers, ultrasound transmitters need to generate higher voltage signals and the receiver's dynamic range must also be large enough to amplify the low echo signals obtained from the transducers [4, 5]. Therefore, it is highly desirable that the performances of the ultrasound systems including protection circuits be optimized and improved.

As shown in Fig. 1, the protection circuits for an ultrasound system are composed of the expander and limiter. The expander prevents the noise signals originating from the transmitter from reaching the transducer and the limiter prevents high voltage pulse signals produced by the transmitter from reaching the receiver. Normally, the expander consists of a single, crossed diode pair [6]. However, since VHF transducers require abnormally high voltage excitation pulses, two crossed diode pairs ($D_1$–$D_4$) are needed to block the noise signals more sufficiently as shown in Fig. 1.

In the resistor circuit (Fig. 1a), a single crossed diode pair works ($D_5$ and $D_6$) as an open and closed switch for low and high voltage pulses, respectively. Therefore, the discharged high voltage signal passes through a single diode pair ($D_5$ and $D_6$) into ground. The resistor circuit is a simple structure without any external power supply, which keeps it free from the noise caused by DC power supplies [6]. However, this scheme results in higher signal conduction loss and excessive ring down in the VHF range and these phenomena are highly problematic for low sensitivity VHF transducers [7].

To overcome these issues, bridge circuit protection schemes (Fig. 1b) have been developed. The four bridge diodes ($D_7$–$D_{10}$) are forward biased by a DC power supply. High voltage signals pass through a single diode pair ($D_{11}$ and $D_{12}$) into ground while low voltage echo signals pass through to the receiver. In this protection circuit, a DC power supply is needed to bias the diode–bridge structures. Additionally, control logic circuits need to be implemented to reduce the ring down of the echo signal [6, 8]. One drawback of the bridge circuit protection scheme is that using a DC power supply introduces noise into the transducer, thus lowering the signal-to-noise ratio in the ultrasound system.

To avoid these undesirable byproducts, we propose a new protection circuit design that utilizes power MOSFET devices, which we call a MOSFET circuit. The positive and negative high voltage signals coming from the expander can flow through the upper ($N_1$–$N_4$) and lower sides ($N_5$–$N_8$) of the power MOSFET devices, respectively. After that, unwanted high voltage signals flow to ground through a single diode pair ($D_{13}$–$D_{14}$). The only series connected MOSFET design may not be enough to block higher noise signal originating from the transmitter and it could increase the IL which is a critical problem for VHF transducers with low sensitivity. To increase isolation between the transmitter and receiver, and maximize the sensitivity of the echo signal, two more power MOSFET devices $N_2$ and $N_7$ were placed in parallel to MOSFET devices $N_3$ and $N_6$. Therefore, this whole structure was designed to pass through an ideal echo signal pattern as shown in Fig. 1c.

In order to use the protection circuits for ultrasound applications, all the components must have a high power tolerance. This is because the protection circuit must absorb the high voltage pulse signals originated from the transmitter. Thus, 50 W 50-Ω power resistors (R, $R_{vdd}$ and $R_{vss}$) (MP850-50.0–1 %, Caddock Electronics, Riverside, CA) and several single diode pairs ($D_1$–$D_{12}$) (PMBD 7000, NXP Semiconductors, Netherlands) with 100 V breakdown voltage and fast recovery time (< 4 ns) were used to construct the protection circuits. For the bridge circuit, 100 nF capacitors ($C_1$ and $C_2$) with 200 V breakdown voltage rating and a linear regulated DC power supply (Agilent Technologies, Santa Clara, CA) were used. For the MOSFET circuit, several power MOSFET devices (IRF5801, International IOR Rectifier, El Segundo, CA) which have 200 V breakdown voltage and 4.8 A maximum pulse current were used.

## The equivalent circuit models

In the ultrasound protection circuit, the expander circuit normally passes high voltage pulse signals and blocks low voltage noise signals traveling from the transmitter to the transducer. Conversely, the limiter circuit passes low voltage echo signals from the transducers and blocks high voltage pulse signals. To predict the behavior of the limiter circuit, both high frequency small signal (HFSS) and large signal (LS) equivalent circuit models were derived [9]. Using a HFSS equivalent circuit model of the power MOSFET device [10], the HFSS equivalent circuit model of the limiter was constructed as shown in Fig. 2a. This equivalent circuit model shows that the MOSFET limiter behaves as a high pass filter, thus minimizing the IL at higher frequency operation. As shown in Fig. 2a, the equivalent HFSS model of the MOSFET circuit has relatively low parasitic resistance and capacitance [(5/4)*$r_o$ and (4/5)*($C_{gs}$+$C_{ds}$)] even though this circuit was constructed using eight power MOSFET devices. This was possible due to the unique arrangement of the power MOSFET components within the circuit. Thus, this novel configuration can improve the performance of the protection circuit. In order to estimate the IL vs. frequency of the MOSFET circuit, the −3 dB cut-off frequency was derived from HFSS equivalent circuit model.

$$\mathrm{f}_{-3dB}=[2\pi\cdot((1/2)\mathrm{R_d}//\mathrm{R_{pre}}+(5/4)\mathrm{r_o})\cdot((4/5)(\mathrm{C_{ds}}+\mathrm{C_{gs}})+2\mathrm{C_d})]^{-1} \quad (1)$$

where $r_0$ is the parasitic drain-source resistance, $C_{ds}$ and $C_{gs}$ are the parasitic drain-source and gate-source capacitance of the MOSFET, $R_d$ and $C_d$ are the parasitic clamping diode resistance and capacitance and $R_{pre}$ is the ideal receiver input resistance.

In order to predict the THD and transient behavior of the MOSFET circuit, the LS equivalent circuit model of the MOSFET circuit was constructed using the LS equivalent circuit model of the gate-drain connected power MOSFET (Fig. 2b and c) [11]. The designed three-stage structure could reduce parasitic capacitances, thus minimizing the response time of the MOSFET circuit and also increase isolation performance. In order to estimate the IL and THD of the protection circuit, the PSpice circuit program (Cadence Design System, San Jose, CA) was used. The IL and THD can be calculated as

$$\mathrm{IL}=20\cdot\mathrm{Log}\left(\frac{\text{Output voltage with devices}}{\text{Output voltage without devices}}\right) \quad (2)$$

$$\mathrm{THD}=20\cdot \mathrm{Log}\frac{(V_2)^2+(V_3)^{2\cdots}+(V_n)^2}{V_1{}^2} \quad (3)$$

where $V_1$, is the amplitude of the fundamental signal, $V_2$, $V_3$ and $V_n$ are the amplitude 2nd, 3rd, nth harmonic signals, respectively of the device. For THD calculation, the 1st–3rd harmonics were included.

The estimated ILs of the resistor, bridge and MOSFET circuits are −6.4, −0.6 and −0.5 dB, respectively using 120 MHz, 50 $mV_{p-p}$ input signal. Using the manufacturer datasheets of the power MOSFET and diode devices as a reference, the calculated cut-off frequency of the MOSFET circuit is 24.0 MHz. The simulated and measured cut-off frequencies of the MOSFET circuit are also 22.6 and 20.7 MHz, respectively. The estimated THDs of these circuits are −104.6, −109.2 and −117.2 dB, respectively using 120 MHz, 0.8 $V_{p-p}$ signal. THD analysis also revealed discrepancies between measured and predicted data. These discrepancies were caused by the lack of accurate distortion source from model libraries such as the semiconductor components, test equipments and coaxial cables [12]. The transient response time (recovery time) data were not simulated because the library data of the commercial pulser is not available from the manufacturer. Therefore, the simulated data are provided here only for reference.

## Protection circuit evaluation and discussion

A continuous sine wave signal from a function generator (AFG3251, Tektronix, Beaverton, OR) was applied to the limiter and the output waveform of the limiter was recorded by an oscilloscope (LC534, LeCroy, Chestnut Ridge, NY) which has six bit resolution and 1 GHz sampling rate. As shown in Fig. 3a, the IL of the resistor circuit becomes worse as the frequency increases and the resistor circuit behaves as a low pass filter. Thus, the bridge or MOSFET circuit might be better choice for VHF transducers since they typically have lower sensitivity. However, the IL of the bridge and MOSFET circuits behave as a high pass filter. Above 20 MHz, the MOSFET circuit showed lower IL (−3.7 dB at 20 MHz) than the resistor circuit does (−4.2 dB at 20 MHz). Above 40 MHz, the MOSFET circuit has lower IL (−1.8 dB at 40 MHz) than the bridge-diode-based limiter does (−1.9 dB at 40 MHz). The MOSFET circuit clearly demonstrated lower IL (−1.0 dB) than the resistor and bridge circuits (−6.3 and −2.2 dB) when a 120 MHz, 50 $mV_{p–p}$ sine wave input was applied. This is because the parasitic capacitances of the MOSFET circuit were minimized in order to lower IL at high frequency operation.

Since the diode and power MOSFET devices may generate the signal distortions and harmonics, we calculated THD of the devices. Figure 3b shows the THD vs. frequency of the circuits. The THD performance of the resistor and MOSFET circuits (−85.5 and −85.8 dB at 40 MHz) is better than that of the bridge circuit (−81.7 dB at 40 MHz) at 40 MHz and higher. The THD performance of the MOSFET circuit is better that that of other schemes above 80 MHz because of its reduced parasitic impedance for higher frequency operation. Figure 3c shows the THD vs. voltage of the protection circuits. The MOSFET circuit exhibits lower THD (−69.8 dB) than the resistor and bridge circuits (−59.3 and −57.7 dB) when a 120 MHz 0.8 $V_{p-p}$ input signal was applied. The improved performance is due to the low parasitic impedance of the MOSFET circuit.

Figure 3d shows the transient response time (TRT) or recovery time (RT) which is a measure of the circuits' ability to block high voltage signals. The protection circuit transfers high voltage signals from the power amplifier through the expander where the limiter clamps the signal in order to protect the receiver from the high voltage pulse [13]. The TRT was measured to evaluate the transient response of the protection circuits. For VHF transducers, the distance between the transducer and target is typically less than 2 mm and because of this very short echo path length the transmitted discharged pulse may interfere with the received echo signals. Thus, a faster TRT is highly desirable in order to avoid received echo signal distortion with high voltage discharge pulses. The TRT is the elapsed time from when the input signal starts to when the output signals reaches +/− 0.1 % point of the final output voltage of the device. 120 MHz, 70 $V_{p-p}$ 3 cycle sine wave signal from the 50-dB power amplifier (75A250A, Amplifier Research, Souderton, PA) was applied to the expander and limiter while the measured output waveform was recorded by the oscilloscope. The MOSFET circuit showed higher voltage reduction (3.6 $V_{p-p}$) and faster TRT (78 ns) than the resistor (4.8 $V_{p-p}$ and 91 ns) and bridge circuits (6.8 $V_{p-p}$ and 160 ns). During high voltage signal emission, the bridge diodes has a relatively lower impedance which allows high voltage signals to pass through without any significant signal loss. However, the eight uniquely-connected MOSFET devices consume more power relative to bridge diodes before the signal reaches the clamping diodes ($D_{13}$ and $D_{14}$) since the displacement current can cause sufficient voltage drop across the parasitic impedances of the MOSFET [14, 15]. Based on the measured data in Fig. 3d, the MOSFET circuit showed relatively lower signal amplitudes which confirm the theoretical description.

In order to further evaluate the performance of the protection circuits, we measured the pulse-echo response of the system using a VHF transducer fabricated in our lab. A single element 120 MHz $LiNbO_3$ transducer with a 1 mm aperture size and 1.4 mm focal distance was fabricated to test the protection circuits. The transducer was directed toward a flat, polished quartz target located at the focal point. The function generator sent a three cycle 120 MHz, 0.3 $V_{p-p}$ pulse signal to the power amplifier in order to trigger the transducer. The transmitted acoustic pulse was reflected off the quartz target and the received echo signals were amplified by the 36 dB gain preamplifier (AU-1114, Miteq, Hauppauge, NY). As shown in Fig. 3e and f, the echo amplitude and spectrum bandwidth of the transducer using the MOSFET circuit improved by 252.1 and 50.9 %, respectively with respect to those values of the transducer using the resistor circuit since the MOSFET circuit provided lower IL and THD than other schemes at 120 MHz operation.

## Conclusion

The discrete power MOSFET components have undesired parasitic impedances caused by packaging and boding pads. Integrated circuit fabrication may be good solution to reduce the parasitic impedances by implementing several components in one single chip. Therefore, the performances such as IL and TRT could be further optimized for high frequency ultrasonic transducer applications.

The MOSFET circuit behaves as a kind of high pass filter, thus sacrificing the performances in the relatively low frequency range while improving the performances in the high frequency range. In order to use the MOSFET circuit for low frequency ultrasound applications, the −3 dB cut-off frequency of the circuit need to be further decreased by increasing power MOSFET parasitic impedances. However, this method could deteriorate the IL and THD performances of the MOSFET circuit.

A new protection circuit using power MOSFET devices is reported for VHF ultrasound transducer applications. In order to construct a high performance protection circuit for low sensitivity VHF transducers, power MOSFET devices must have a low gate-source and low drain-source capacitances since these parameters are all related to signal loss and distortion. The resistor and bridge circuit showed relatively lower IL than MOSFET circuit at low frequency range. However, they showed clearly worse performance than the MOSFET circuit at VHF operation due to low IL, THD and TRT performance. The MOSFET circuit has the lowest IL (−1.0 dB) and THD (−69.8 dB) and fastest TRT (78 ns) at 120 MHz. For the pulseecho measurement, the sensitivity and bandwidth of the 120 MHz $LiNbO_3$ transducer using the MOSFET circuit were improved by 252.1 and 50.9 % over the resistor circuit. Therefore, these results confirm that the MOSFET circuit is an excellent alternative solution as protection circuits particularly for VHF ultrasound transducer applications.

## Acknowledgments

The authors thank Mr. Thomas Cummins for his editing contribution. This research was supported by National Institutes of Health Grant # P41–EB002182.

## References

1. Hsu HS, Benjauthrit V, Zheng F, Chen R, Huang Y, Zhoua Q, Shung KK. PMN-PT–PZT composite films for high frequency ultrasonic transducer applications. Sensors Actuators A Phys. 2012; 179:121–124.
2. Zhu B, Han J, Shi J, Shung KK, Wei Q, Huang Y, Kosec M, Zhou Q. Lift-off PMN-PT thick film for high-frequency ultrasonic biomicroscopy. J Am Ceram Soc. 2010; 93(10):2929–2931. [PubMed: 21170158]
3. Choi H, Li X, Lau ST, Hu CH, Zhou Q, Shung KK. Development of integrated preamplifier for high-frequency ultrasonic transducers and low-power handheld receiver. IEEE Trans Ultrason Ferroelectr Freq Control. 2011; 58(12):2646–2658. [PubMed: 23443700]
4. Güler I, Savaş Y. Design parameters of pulsed wave ultrasonic doppler blood flowmeter. J Med Syst. 1998; 22(4):273–278. [PubMed: 9690183]
5. Amer M. Novel design of low noise preamplifier for medical ultrasound transducers. J Med Syst. 2011; 35(1):71–77. [PubMed: 20703584]
6. Fuller MI, Blalock TN, Hossack JA, Walker WF. Novel transmit protection scheme for ultrasound systems. IEEE Trans Ultrason Ferroelectr Freq Control. 2007; 54(1):79–86. [PubMed: 17225802]
7. Moore, TC.; Suorsa, V.; Masters, D. Preamplifier and protection circuit for an ultrasound catheter. US Patent 6. 2003. p. 432
8. MD0100DB1 datasheet. Supertex Inc; 2010. High Voltage Protection 8-Channel T/R Switch Demo board.
9. Linder, S. Power semiconductors. EPFL Press; Portland: 2006.
10. Nienhaus HA, Bowers JC, Herren PC Jr. High power MOSFET computer model. IEEE PESC Rec. 1980:97–103.

11. Minasian RA. Power MOSFET dynamic large-signal model. IEEE Proc. 1. Solid-State Electron Devices. 1983:73–9.
12. Vuolevi, J.; Rahkonen, T. Distortion in RF power amplifiers. Artech House; Norwood: 2003.
13. Zhu BP, Wu DW, Zhang Y, Ou-Yang J, Chen S, Yang XF. Sol–gel derived PMN-PT thick films for high frequency ultrasound linear array applications. Ceram Int. 2013; 39(8):8709–8714.
14. Grant, DA.; Gowar, J. Power MOSFETs theory and applications. Wiley-Interscience; New York: 1989.
15. Baliga, BJ. Advanced power MOSFET concepts. Springer; New York: 2010.

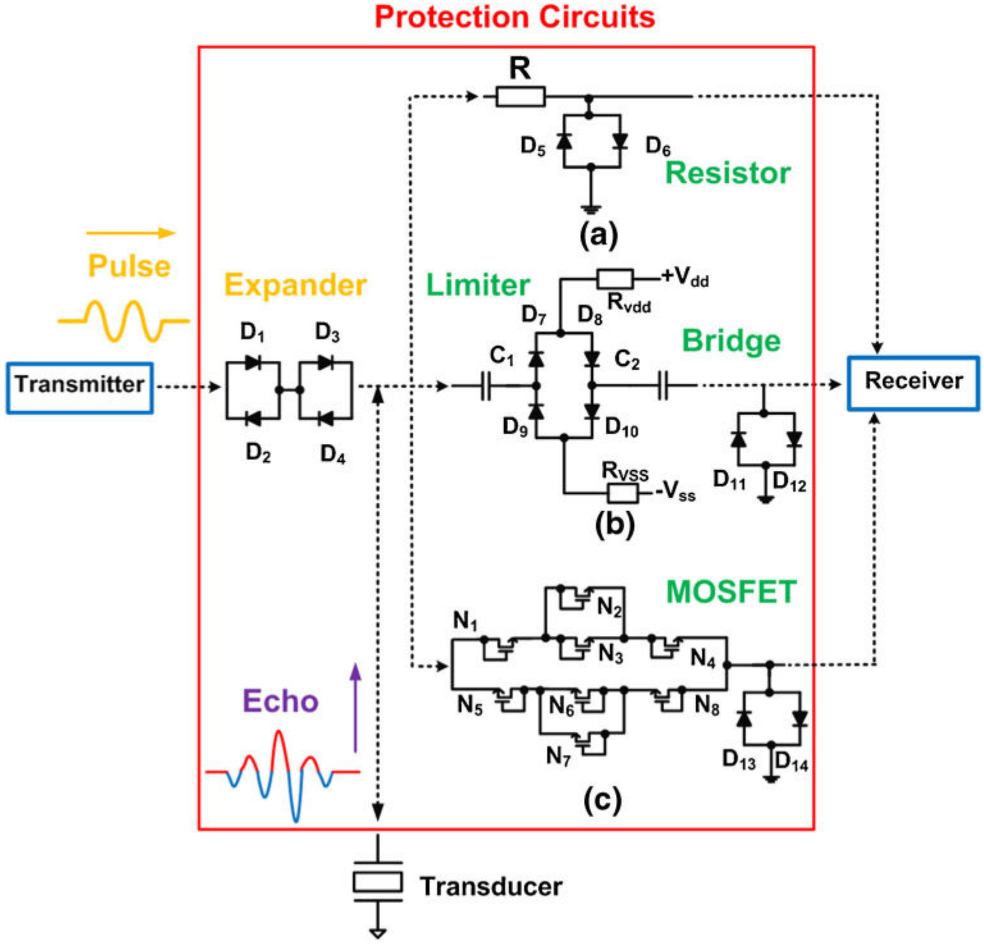


**Fig. 1.**

Protection circuit architectures: **a** resistor, **b** bridge and **c** MOSFET protection circuits

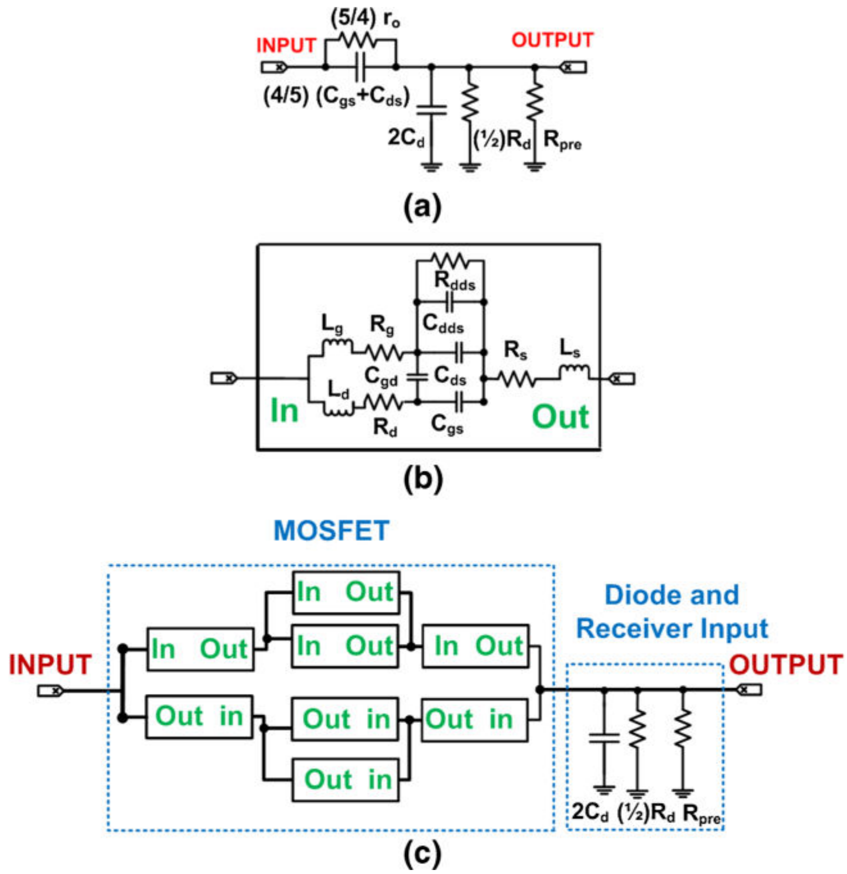


**Fig. 2.**

**a** HFSS equivalent circuit modelof the MOSFET circuit, **b** a LS equivalent circuit model of the power MOSFET and **c** LS equivalent circuit model of the MOSFET circuit. **Lg, Ld and Ls are the parasitic inductances, Rg, Rd and Rs are the parasitic resistances of the power MOSFET, Rdds and Cdds are the parasitic resistance and capacitance of the power MOSFET protection diode

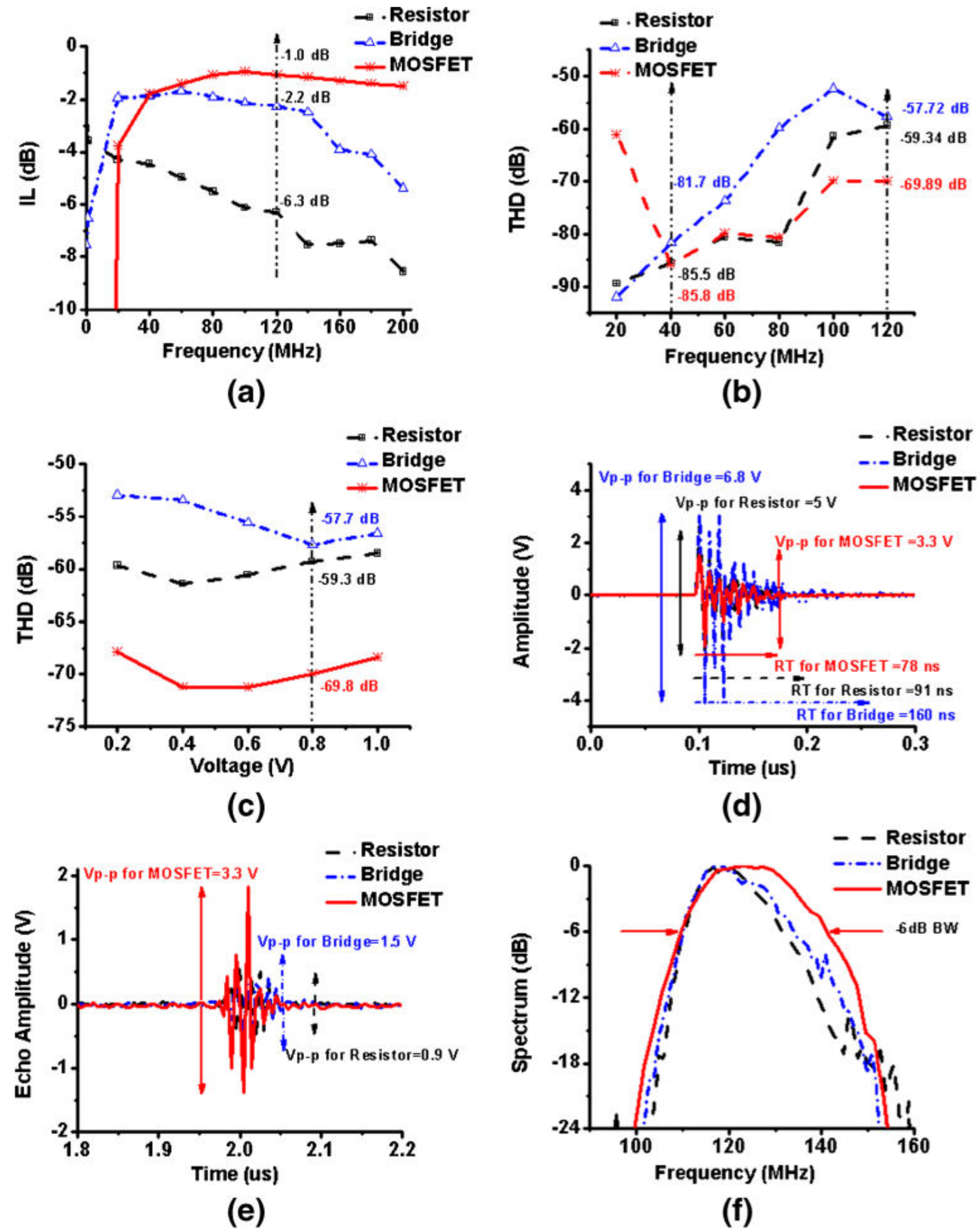


**Fig. 3.**

Protection circuit measurement results. **a** IL vs. frequency when a 50 mV continuous sine wave was applied, **b** THD vs. frequency when a 0.8 Vp-p continuous sine wave was applied. **c** THD vs. voltage when 120 MHz continuous sine wave was applied, **d** TRT when 120 MHz, 70 Vp-p 3 cycle pulse signal was applied, **e** echo amplitude and **d** spectrum of the transducer using the protection circuits with 120 MHz pulse signal from the power amplifier. *Resistor, Bridge and MOSFET stand for the resistor (*dash*), bridge (*dash-dot*) and MOSFET (*straight*) protection circuits, respectively