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RESEARCH ARTICLE

Design and Analysis of an Adjustable Diode-Integrated Waveguide-Based Electromagnetic Pulse Limiter for Microwave Receiver

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ABSTRACT A new waveguide-based diode limiter is proposed to protect microwave-amplifying receivers from high-power electromagnetic pulses. The diode limiter was designed and fabricated to exhibit low insertion loss for normal signals while effectively blocking high-power transient signals. The proposed structure incorporates a diode element positioned between vertically connected cylinders inside the waveguide, with a square-integrated structure symmetrically placed on both the top and bottom. The diode element is inserted beneath a thin rod. Under low incident power, the diode remains inoperative, maintaining an electrically open state. In the presence of high incident power, the diode activates, transitioning into an electrically short state. The newly proposed structure enables the cylinder's vertical movement, providing the advantage of adjustability to shift the center operating frequency of the diode limiter. It incorporates a band-pass filter structure for normal signals and a band-stop filter characteristic for transient signals. Moreover, the symmetrical square-integrated structure is employed to concentrate the surface current at the diode element, enhancing the changing state of the diode limiter. This configuration demonstrates a low insertion loss of 0.38 dB for normal signals and a blocking coefficient of 8 dB for transient signals at the 5.68 GHz operating frequency.

INDEX TERMS Electromagnetic pulse, diode limiter, waveguide.

I. INTRODUCTION

High-power electromagnetic pulses (EMP) pose a significant threat to modern society, which is heavily reliant on electronic devices. Social infrastructure controlled by electronic devices such as power, communication, gas/water supply, etc. have an affinity with each other. Any issues in one area can potentially lead to widespread system disruptions, earning EMP the moniker of a blackout war. Evidently, most of the EMP energy of naturally occurring lightning EMP is mostly distributed below 1 MHz in the frequency band [1], and that of nuclear EMPs generated by nuclear explosions at high altitudes, most of the EMP energy is distributed below 1 GHz [2]. Advances in science and technology have extended the EMP threat above 1 GHz due to artificially created high-power electromagnetic pulse generators like gyrotrons [3], magnetrons [4], and solid-state power amplifiers [5]. To process communication data at high speed, communication frequencies in a higher frequency band are required [6]; furthermore, in object identification systems, high-output power, high-frequency bands with short wavelengths are also used to increase resolution of identification [7].

Consequently, the frequency band used is gradually increasing. Furthermore, in the communication frequency

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band above 1 GHz, transmission lines are gradually being used from the coaxial type to the waveguide type due to high-frequency transmission line loss [8]. Waveguides, primarily shaped with cavity pipes, offer advantages such as low insertion loss in high-frequency bands and facilitates easy designing of the performance desired by the user [9]. However, as the system moves to higher frequency bands, the output power signal, handled by the system itself, decreases, and the microwave receiver must accommodate lower signals [10], [11]. This necessitates the microwave receiver's primary function to amplify signals of lower magnitude. Yet, the EMP threat described above mainly causes problems in these receiver amplifier stages. The characteristic of amplifying a low-level normal signal exhibits high vulnerability to EMP transient signals with high power level; moreover, when it is exposed to EMP, the microwave receiver temporarily stops or causes permanent failure [12], [13], [14]. For this reason, a device that can protect the microwave receiver is becoming essential in communication systems.

EMP protection devices based on waveguides can be broadly categorized into two types. Firstly, the plasma limiter safeguards the microwave receiver by facilitating plasma discharge within the waveguide. Normal signals of low magnitude smoothly pass through without inducing plasma discharge and are transmitted with low insertion loss. In contrast, EMP—a substantial transient signal—triggers plasma discharge by concentrating the electric field at a specific point within the waveguide, thereby altering the mode or resonance characteristics [15]. The plasma limiter exhibits stable operation, effectively reflecting most power, even when transient signal incidence exceeds 10 kW. However, it remains stable only when the incident pulse magnitude is approximately 200 W or more, contingent on the plasma limiter's shape and gas pressure. This value exceeds the acceptable range for microwave receiver of a communication system that typically operates in magnitude of μW units [16]. Furthermore, during the initial stages of plasma limiter operation, a slight leakage pulse may be transmitted due to delayed response time, posing a threat to the microwave receiver. To counteract this issue, a diode limiter becomes necessary.

Typically, diode limiters rely on semiconductor-based PIN diodes. They offer advantages such as a short response time and the ability to respond even to low-power incident waveforms. Ongoing research efforts aim to improve diode limiter performance by reducing the recovery time of the Schottky diode device used in the limiter [17], exploring diamond-based devices with favorable thermal characteristics [18], or analyzing degradation characteristics within the PIN diode device [19]. Alternatively, some studies focus on altering the shape of a microstrip-line-based filter [20], while others implement a limiter function in the form of an energy-selective surface by integrating diode elements at the antenna end [21], [22], [23]. There's also research that implements an EMP protection limiter by creating a slot shape on a PCB board within a waveguide and placing a diode element in the center [24].

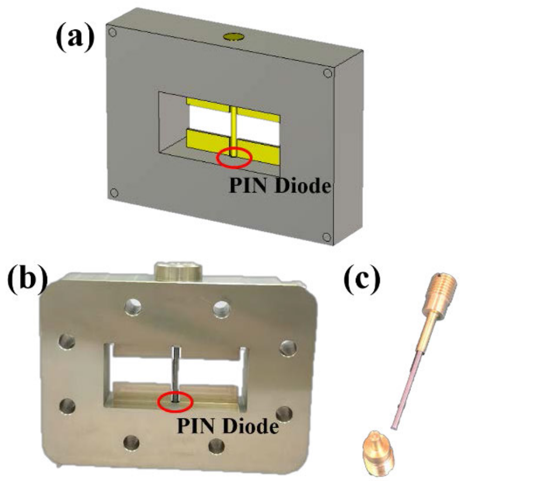

FIGURE 1. (a) Schematic image of diode limiter, (b) demonstrated diode limiter and (c) electrode structure with diode holder.

In this study, a cylindrical diode limiter was developed with low insertion loss for normal signals and a high reflection coefficient for transient signals. A novel design structure was created, featuring the insertion of a diode element between vertically connected cylinders inside the waveguide. Notably, the position of the cylinder can be adjusted vertically, providing the capability to fine-tune the center frequency of the diode limiter. This adjustment imparts band-pass filter characteristics for normal signals and band-stop filter characteristics for transient signals. This represents a departure from prior research where the target frequency remained fixed. Additionally, to decrease the response voltage of the diode device, a new structure was introduced, incorporating four square-integrated structures symmetrically arranged around a cylinder. Simulation and test bed results confirmed the enhanced operating performance of the diode limiter.

II. DESIGN OF THE DIODE LIMITER

The diode limiter is designed to have a low insertion loss for normal signals and a high blocking coefficient for high-power EMP inputs. A high blocking coefficient stands for insertion loss of large power response. A schematic and demonstration of the diode limiter are shown in Fig. 1. A diode is inserted under a thin rod. As shown in Fig. 1(c), both upper and lower parts of electrode structure have screw line, and in other areas of the electrode structure have margin to mechanically move upward or downward. In addition, lower part of electrode structure has holder shape to place diode element which reduce the error of installment. When a low incident power is applied, the diode does not operate and is in an electrically open state. When a high incident power is applied, the diode operates and becomes electrically short. A waveguide-type diode limiter was fabricated using the dip-brazing method, and the assembly parts were connected by soldering. The back-to-back diode set was obtained by soldering two diode elements.

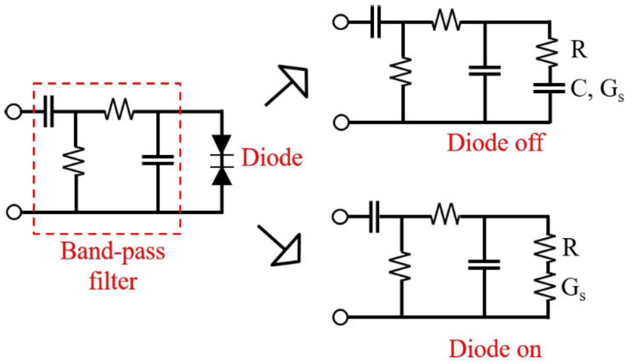

FIGURE 2. Equivalent circuit of the diode limiter.

The equivalent circuit of the proposed diode limiter is illustrated in Fig. 2. The design parameters of the diode limiter can be represented in parallel as band-pass filter elements with back-to-back diodes in parallel. In a waveguide system, the traveling wave propagates with a phase variation of 360 degrees, and the electric field polarization varies from upward to downward. In the case of a single diode element, the low-power impulse test result of the diode limiter has shown an unstable ON-state, which must be in the OFF-state. Because for the low-power incident pulse, the single-diode element-based limiter exhibits forward-bias characteristics for the 180-degree phase. With the back-to-back diode set, the result has shown ideal characteristics. For the low power state, which is the PIN diode in OFF-state, the PIN diode has shown reverse bias characteristics. In both upward and downward polarization states, the first PIN diode reacts as a forward-bias state, where only the low turn-on resistance of the diode element is retained. The second PIN diode operates as a reverse-bias state and can be considered an open circuit with the capacitor element. In the high-power state, the first PIN diode also reacts as a forward-bias state, and the second PIN diode operates as a reverse-bias with the breakdown state. This ON-state can be considered as short circuit with the serial connection of resistor elements.

The changes in the transfer characteristics based on the design parameters of the diode limiter were predicted. Electromagnetic simulation of the diode limiter was performed using commercial software (CST). Within the waveguide and diode model, the plane wave was placed on the front side. The electromagnetic response of the device was detected by the probe where it was located on the opposite side. The boundary conditions of simulation were set as a perfect electrical conductor at the top and bottom, and a perfect magnetic conductor on the left and right. The waveguide size was 22.148 $\times$ 47.548 mm, representing the WR187 standard. In Fig. 3, design parameters related to the electrodes that influence the resonance frequency are shown, and it relates to the band-pass filter parameters in Fig. 2. The parameters B, C, E, and F have sizes of 5 mm, 13 mm, 6 mm, and 6 mm, respectively. This part is mechanically fixed to the waveguide body and does not affect the transfer characteristics.

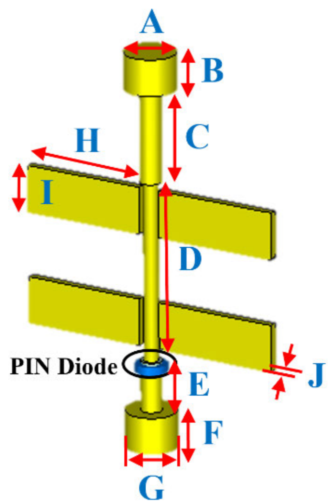

FIGURE 3. Schematic view of the design parameter in diode limiter.

Parameters A and G have a size of 3.5 mm and do not impact normal signal transfer, but with down-sizing, the resonant frequency shifts to the lower frequency regime for high-power EMP. Parameter D is the length of the electrode visible within the waveguide, having a minor effect on normal signal transfer with a size of 26 mm. For high-power EMP, it has a major effect when the electrode is shortened, causing the resonant frequency to shift to a higher frequency regime. Parameters H and I represent the sizes of the square-shaped structure next to the electrode, with sizes of 17 mm and 6.5 mm, respectively. Parameter H does not affect high-power EMP transfer but has a minor effect on normal signal transfer. Parameter I has a major effect on both normal and high-power EMP transfers; as it increases in size, the resonant frequency shifts to the lower frequency regime. Parameter J represents the thickness of the square-shaped structure with a size of 1 mm. This has a major effect on the high-power EMP transfer when it gets thicker the resonant frequency increases to a lower frequency regime. For normal signal transfer, as the thickness decreases, the resonant frequency shifts to a higher frequency regime.

The electromagnetic simulation results of normal- and high-power EMP transfer are shown in Fig. 4. In the EMP OFF-state, the normal signal experiences an insertion loss of 0.36 dB at 5.68 GHz, with insertion loss less than 1 dB in the frequency range from 5.10 GHz to 6.76 GHz. Measurements were performed using a network analyzer, and the demonstrated diode limiter exhibits an insertion loss of 0.38 dB at 5.68 GHz. The insertion loss remains less than 1 dB in the frequency range from 5.45 GHz to 6.99 GHz, with a difference of less than 0.02 dB from simulation due to fabrication error. In the EMP ON-state, where high-power EMP or an incident transient pulse is applied, the diode reacts to the breakdown state, becoming electrically short. As a result, the band-stop filter characteristic is shown, with a 38 dB blocking coefficient at 5.68 GHz. The simulated

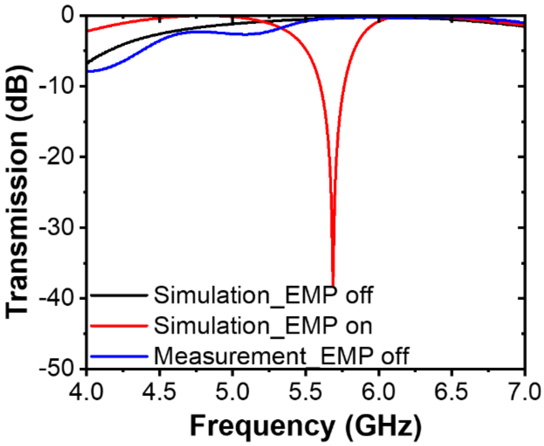

FIGURE 4. Simulation and transmission measurement results of the square-shaped structure integrated diode limiter.

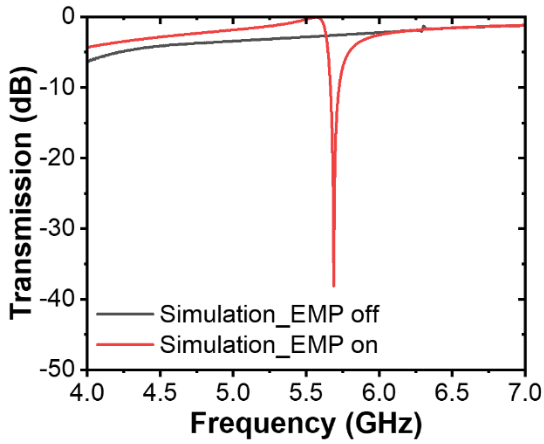

FIGURE 6. Simulation result of pole-shape diode limiter.

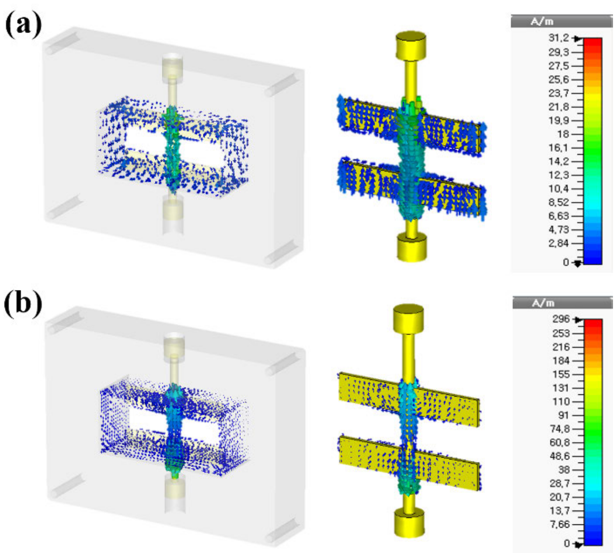

FIGURE 5. Simulated surface current density of square-shaped diode limiter; (a) EMP off (b) EMP on.

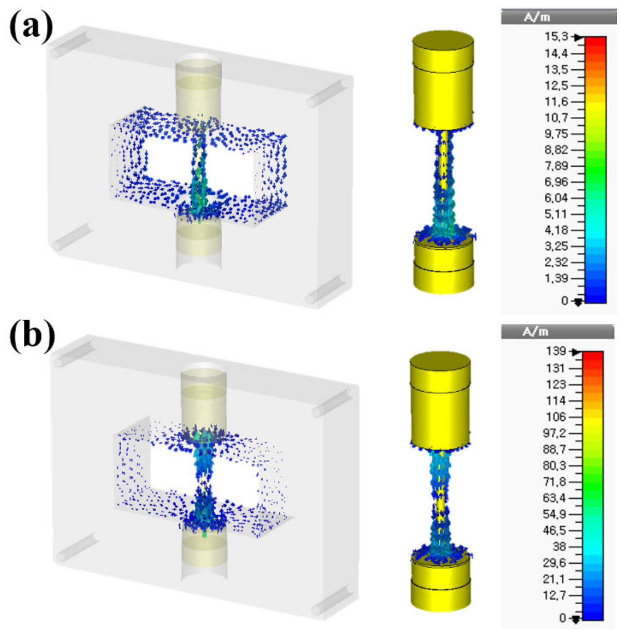

FIGURE 7. Simulated surface current distribution of pole-shaped diode limiter; (a) EMP off (b) EMP on.

surface current density of the square-shaped diode limiter is given in Fig. 5. In the EMP OFF-state, the surface current is evenly distributed, with a maximum surface current density of 31.2 A/m at the electrode. In the EMP ON-state, the surface current concentrates at the diode part, allowing the diode to easily change to the ON-state, even at low incident power. It has a maximum surface current density of 296 A/m, almost 10 times higher than that of the EMP OFF-state.

To compare the role of the square-integrated structure, the pole-shaped diode limiter simulation results are given in Fig. 6. In the EMP OFF-state, the normal signal experiences an insertion loss of 2.61 dB at 5.68 GHz, with insertion loss less than 3 dB and above 2 dB in the frequency range from 5.36 GHz to 6.16 GHz. In the EMP ON-state, the band-stop filter characteristic is shown, with a 38 dB blocking coefficient at 5.68 GHz. Compared to the square-shaped structure, it exhibits a 2.25 dB higher insertion loss for normal signal transfer and a narrower bandwidth response for high-power EMP. Moreover, the design parameters are limited because only the pole structure inside the waveguide affects the transferring characteristics. Therefore, it has the limitation of lowering the insertion loss for normal signal transferring. The simulated surface current density of the pole-shaped diode limiter is given in Fig. 7. The surface current distribution was similar to that of the square-integrated structure, with maximum surface current densities of 15.3 A/m and 139 A/m for the EMP OFF and ON states, respectively. The maximum value of the surface current density for the pole shape was half that of the square-integrated structure, and it is assumed that higher power is required to change the state of the diode limiter.

Figure 8 shows the transferring characteristics of the adjustable diode limiter. The electrode structure is

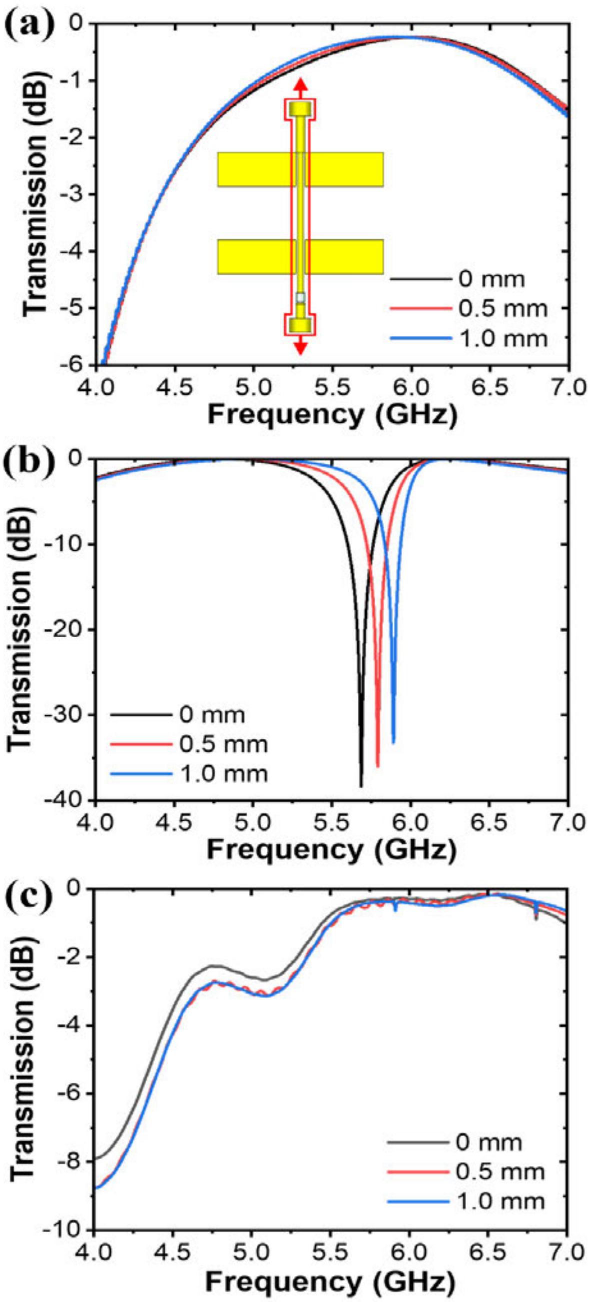

FIGURE 8. Simulation results of the square-shaped structure integrated adjustable diode limiter; (a) EMP off (b) EMP on. (c) Transmission measurement results of the adjustable diode limiter.

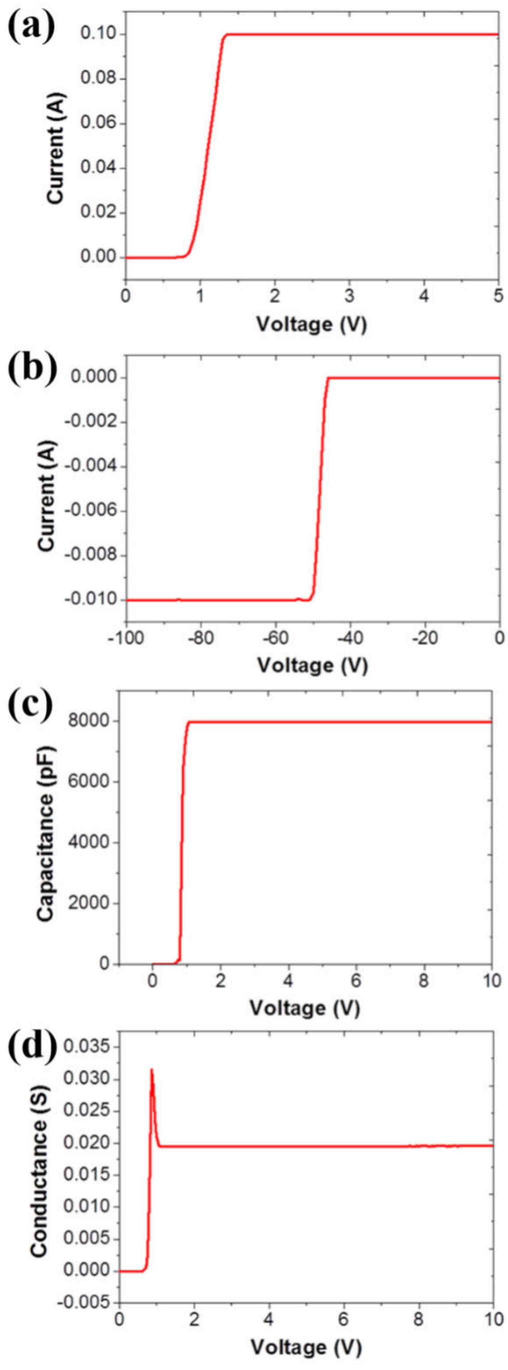

FIGURE 9. Current and voltage characteristics of (a) Forward-biased direction and (b) Reversed-biased direction. (c) Capacitance and voltage characteristics of Forward-biased direction and (d) Conductance characteristics.

mechanically isolated from the square shape, providing a margin to move itself upward or downward. The normal signal transferring characteristics are shown in Fig. 8(a). As the electrode structure moves upward by 1 mm, the change in insertion loss is minor. However, as it moves further, the band-pass filter characteristics are distorted. The high-power EMP transfer characteristics are shown in Fig. 8(b). As the electrode structure moves upward by 0.5 mm and 1 mm, the operating frequency of the band-stop filter shifts to a higher frequency regime at 5.71 GHz and 5.89 GHz, respectively. As it moves further, the band-stop filter characteristics are also distorted. The transmission measurements of the adjustable diode limiter are shown in Fig. 8(c).

The insertion loss of normal signal was changed to 0.47 dB and 0.48 dB at 5.68 GHz by movement of 0.5 mm and 1 mm, respectively, and as it moves further, the distortion of transmission was observed.

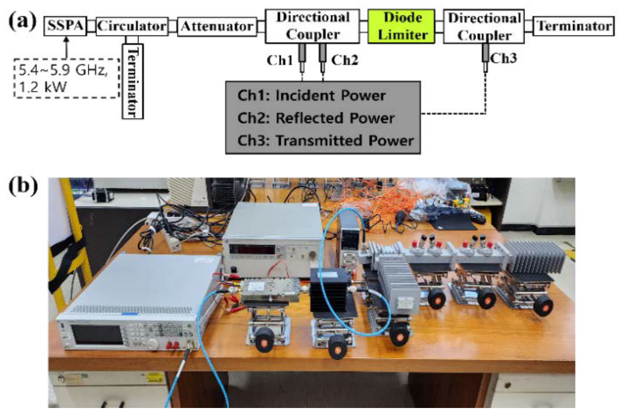

FIGURE 10. (a) Schematic of impulse test bed (b) Equipped impulse test bed.

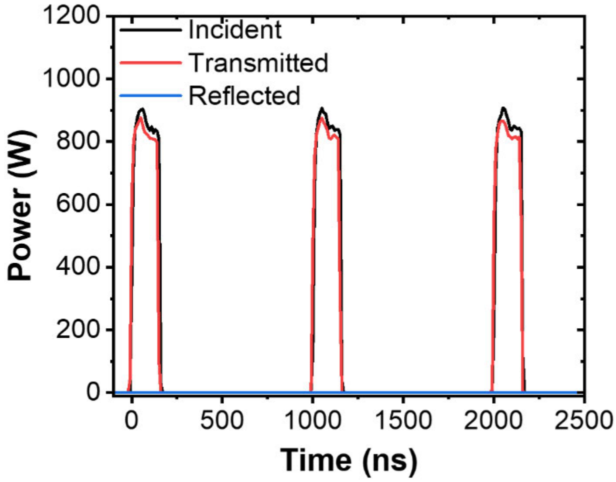

FIGURE 11. Insertion loss of impulse test bed without diode limiter.

The diode adopted in this study had a model number DH60033-03 and was manufactured by the Cobham microwave company. To verify the parameters required for the design of the diode limiter, a semiconductor device analysis was conducted. In Fig. 9(a), it shows that turn-on voltage was measured to be approximately ~0.85 V, and the forward-biased current was measured to be 0.01 A.

Figure 9(b) shows the I-V characteristics in the reverse-bias direction, and the breakdown voltage was measured to be approximately ~50 V. The leakage current was measured to be 0.2 nA at 0 V. Figure 9(c) and 9(d) are the data measuring the capacitance-voltage characteristics and conductance of the diode device. In the forward-bias direction, the capacitance value was measured as 8 nF at 2 V, and the conductivity was measured as 0.019 S at 2 V. In addition, the capacitance value was measured at 0.4 pF at 0 V, and the conductivity was measured as 0.09 uS at 0 V.

The measured values and datasheet of the PIN diode were referenced and entered into the diode model of electromagnetic simulation. These represent the diode parameters in Fig. 2. The required diode parameters were R, C, G_s and I_o where R is the resistance, C is the capacitance, G_s is the conductance when blocked, and I_0 is the reverse current. For low insertion loss in the EMP OFF state, the R value must be high, G_s value must be low, and I_0 value must be low. However, for high-power band-stop attenuation, the R value must be low, G_s value must be high, and I_0 value must be high. These are conflicting results, and ultimately, the goal is to design an appropriate insertion loss and band-stop attenuation.

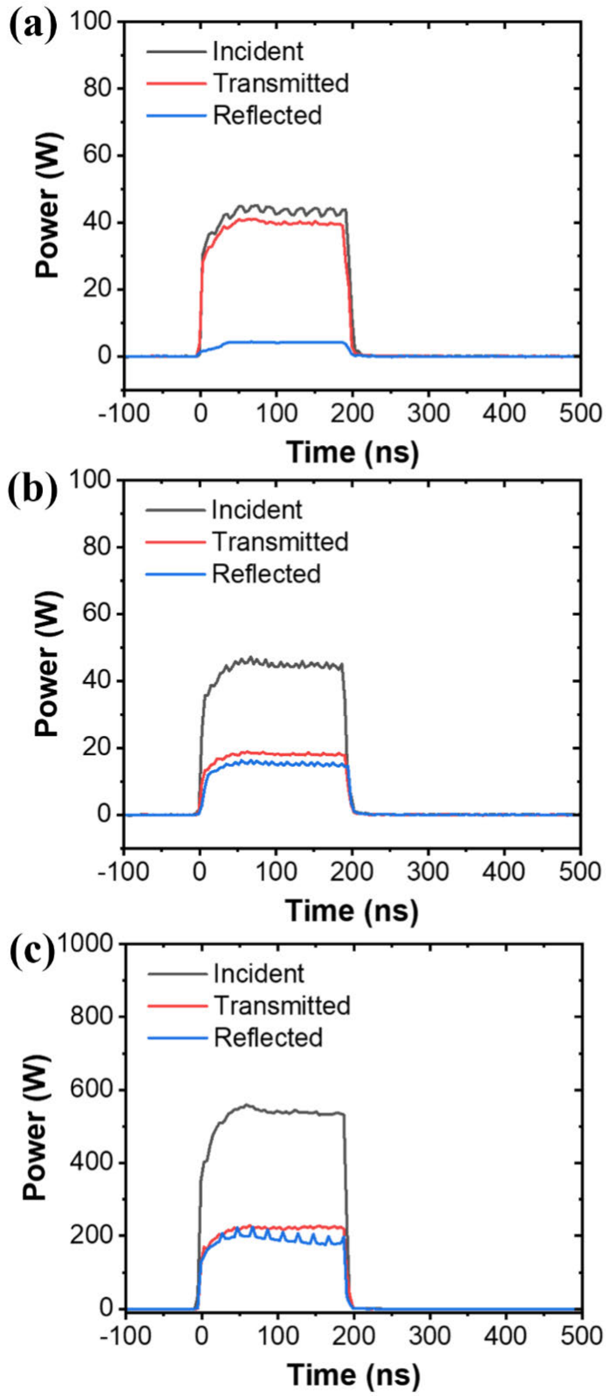

FIGURE 12. Impulse test result; Incident power level of (a) 42 W, (b) 45 W, and (c) 551 W.

TABLE 1. Comparison of the diode limiter performance.

Ref. no.	Frequency (GHz)	Insertion loss of normal signal (dB)	Blocking coefficient for transient signals (dB)	Configuration type
[17]	3.5	< 2	31 @ 37 dBm	Microstrip
[21]	2.1	< 3	7 @ 47 dBm	Microstrip
[24]	2.0	1.83	9 @ 10 dBm	Waveguide
This work	5.68	0.38	8 @ 57 dBm	Waveguide

III. IMPULSE EXPERIMENTS AND RESULTS

To verify the high-power EMP transfer characteristics of the diode limiter, an impulse test bed was established, as shown in Fig. 10. The impulse test was adopted in standard WR187 waveguide size. The signal generator was connected to the solid state power amplifier (SSPA), and the SSPA has 42 dB gain in frequency range of 5.4 GHz ~ 5.9 GHz, and has maximum output power of 1.2 kW. The rise time was 20 ns and the pulse width was 160 ns. A waveguide-type circulator with a terminator was installed to protect the SSPA from reflected power. As the output power could not be controlled by the SSPA, an attenuator was placed to lower the output power from the SSPA. A waveguide-type directional couplers were installed in front of and behind the diode limiter to measure the incident, reflected, and transmitted powers using a power meter. The real-time measurement of power response was monitored by a power meter and a computer. A waveguide-type terminator is installed at the end to absorb the transmitted power. In Fig. 10(b), the equipped impulse test bed is shown and the insertion loss of test bed itself was less than 0.2 dB as shown in Fig. 11

The impulse test results of diode limiter at 5.68 GHz are shown in Fig. 12. As shown in Fig. 12(a), with a 42 W incident pulse, the maximum value of the transmitted pulse was 38 W, and the reflected pulse was 4 W. In Fig. 12(b), for the 45 W incident power level, the diode starts to operate, and the maximum value of the transmitted pulse is 18 W, which has a blocking coefficient of 7.95 dB to the incident value. No delay response was observed in the transmitted power, whereas the plasma-based limiter had a delay response time of 10 ns [15]. The maximum reflected power was 15 W. Therefore, approximately 12 W of power was assumed to be absorbed by Joule heating in the diode device. The incident power increases, as shown in Fig. 12(c). With 551 W incident pulse, the maximum value of the transmitted pulse was 218 W, and the reflected pulse was 202 W. This shows a tendency similar to that shown in Fig. 12(c); therefore, above 45 W, the diode limiter shows a blocking coefficient of 8 dB for high-power EMP. The proposed diode limiter performance is compared to those of previous studies, as presented in Table 1.

IV. CONCLUSION

The proposed diode limiter is based on an adjustable square-integrated-electrode structure. For normal signals at low incident power levels, the diode device remains electrically open, exhibiting bandpass filter characteristics. In the presence of high-power EMP signals, breakdown occurs in the diode device, causing it to operate as an electrically short state. To achieve this, two diode devices are installed with their cathode sides facing each other. The role of the square-integrated shape was compared with a pole-type electrode, and electromagnetic simulation results showed that the concentrated surface current density was two times higher for the square-type diode device. It is assumed that the square-integrated-electrode-structure diode limiter will change the state of the diode device more easily than the pole-type. The movement of the electrode was verified, and a significant variation was observed in high-power EMP transferring from 5.68 GHz to 5.89 GHz by simulation. This characteristic can be further applied to fine-tune the operating frequency of the diode limiter, where fabrication errors can result in a shift in the operating frequency. Impulse testing was performed, and the results showed an 8 dB blocking coefficient. The diode limiter blocked high-power EMP above a 45 W incident power and exhibited a similar tendency up to a 551 W incident power. The proposed diode limiter can be applied to a waveguide system that needs protection from unwanted EMP attacks. When combined with a plasma limiter with higher power capacity but slower response time, the diode limiter can be more suitable. To enhance the blocking coefficient, back-to-back integrated PIN diodes can be developed instead of using soldered diode devices.

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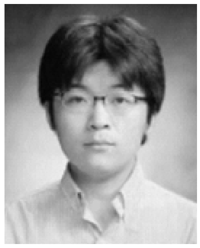

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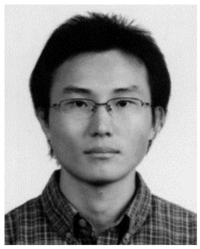

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