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Design and Optimization of a Plasma-Based Power Limiter for 24 GHz Automotive Radar Systems with Enhanced Electromagnetic Interference Suppression

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ARTICLE INFO	ABSTRACT
	Automotive radar systems operating in the 24 GHz band are widely used in Advanced Driver Assistance Systems (ADAS) due to their cost-effectiveness and robust performance across diverse environmental conditions. However, these systems face critical vulnerabilities from electromagnetic interference (EMI) and high-power microwave (HPM) threats, which can degrade detection accuracy. This study presents a novel plasma-based limiter employing a Gas Discharge Tube (GDT) within an optimized K-band waveguide (10.668 × 4.318 mm) filled with Rogers RO3035 dielectric ($\varepsilon r = 3.6$). The design achieves exceptional metrics: 0.9 dB insertion loss and 21.5 dB return loss during normal operation, while providing over 30 dB isolation against HPM signals with a sub-100 ns response time. These characteristics position this solution as an industry-leading protection mechanism for next-generation automotive radars.

1. Introduction

The automotive industry has witnessed a paradigm shift in vehicle safety systems with the advent of radar technology, particularly in the 24 GHz band[1]. Historically, radar systems were first adapted for automotive applications in the 1980s, building upon military-grade millimeter-wave technologies developed during World War II for aircraft detection[2]. These early systems primarily focused on basic collision avoidance, but modern implementations have evolved into sophisticated Advanced Driver Assistance Systems (ADAS) that enable adaptive cruise control, blind-spot monitoring, and autonomous emergency braking[3].

The 24 GHz frequency band has emerged as particularly valuable for automotive applications due to its optimal balance between resolution and

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atmospheric penetration[4]. Compared to higher frequency alternatives like 77 GHz or 79 GHz systems[5], 24 GHz radars offer several distinct advantages: they maintain reliable performance in adverse weather conditions such as heavy rain or fog, where higher frequency signals might experience significant attenuation[4]; they provide sufficient object detection range up to 150 meters while maintaining reasonable component costs; and they benefit from established manufacturing processes that keep production expenses manageable for mid-range vehicles. These characteristics have made 24 GHz radar systems particularly prevalent in the economy and mid-tier vehicle segments, where cost-performance optimization is crucial[6].

However, the widespread deployment of these systems has revealed significant technical challenges that threaten their reliability. EMI represents one of the most pressing concerns, originating from multiple sources within the vehicle's electrical architecture[7]. The internal combustion engine's ignition system generates transient voltages of 50-100 V/m, while high-current switching in electric vehicle powertrains can produce even more severe interference. Additionally, the proliferation of vehicular communication systems, including Dedicated Short-Range Communications (DSRC)[8] and emerging 5G Vehicle-to-Everything (5G-V2X) technologies[9], has created a spectrally congested environment where radar systems must operate. Field studies conducted by the International Telecommunication Union (ITU-R Report M.2410) have demonstrated that these interference sources can degrade radar detection accuracy by up to 30% in urban environments, potentially leading to false alarms or missed detections[10].

Plasma-based limiters have emerged as a promising solution to these challenges, offering distinct advantages over traditional protection methods. Unlike semiconductor-based limiters

that face inherent power handling limitations or ferrite-based solutions that suffer from slow response times, plasma limiters combine high power tolerance with rapid reaction capabilities [11]. The GDT technology at the heart of these devices consists of two or three electrodes housed in a sealed ceramic or glass chamber filled with inert gas(e.g., argon, neon, helium, or a mixture of these) at controlled pressures in the range of a few Torrs up to 100s of Torr[12](for example: 30 Torr for 2049-09-BLF in[13] or 75 Torr for 2045-23-BLF in[14]). When the applied voltage exceeds the breakdown threshold 75–3000 V, depending on electrode spacing and gas pressure inside GDT, the gas ionizes, transitioning from a high-impedance insulating state ($\sim$1–10 GΩ) to a low-impedance conductive state ($\sim$100 Ω) in nanoseconds[14,15]. This transition enables automatic EMI suppression without external triggering, with recovery to the insulating state occurring when the threat subsides. Recent advancements by Semnani et al. [12-16] have demonstrated GDT-based limiters capable of handling 2–20 W power levels in S-band applications, proving the viability of this approach for high-power scenarios.

EMI threats to radar systems manifest through front-door coupling (via antennas or waveguides) or back-door coupling (via cables or structural breaches), causing irreversible damage to sensitive components [17]. GDTs excel in mitigating both coupling types due to their bidirectional symmetry, low capacitance ($\sim$1–2 pF), and ability to impulse discharge currents up to 10 kA[18].

In this paper, we present a novel plasma-based power limiter designed for 24 GHz automotive radar systems to address critical EMI challenges. The proposed solution integrates a GDT within an optimized K-band waveguide filled with Rogers RO3035 dielectric, achieving exceptional performance metrics: 0.9 dB insertion loss, 21.5 dB return loss, and >30 dB isolation against high-

power threats with a sub-100 ns response time. Our design also features field-programmable protection thresholds, enabling customization for diverse radar architectures while maintaining compatibility with standard automotive electrical systems. Through detailed simulations and theoretical modeling, this work advances EMI protection for next-generation Advanced Driver Assistance Systems (ADAS), offering a robust and cost-effective solution for vehicular safety applications.

This paper investigates the performance, advantages, and challenges of a fast plasma-based limiter for automotive radar receivers. The proposed GDT-integrated waveguide limiter, designed for the K-band, offers unique tunability for varying input power thresholds—a first for high-power waveguide limiters. Unlike conventional designs, it eliminates the need for external gas injection, simplifies fabrication, and enables rapid replacement.

2. Design and Simulation of the Plasma-Based Discharge Limiter

Figure 1 shows a system block diagram and limiter integration in automotive radar architecture. The limiter is positioned between the antenna feed and receiver circuitry, intercepting damaging signals before they reach critical subsystems. The operational principle hinges on the dynamic response of a GDT to varying power levels, transitioning between a transparent pass-through state and a reflective plasma barrier.
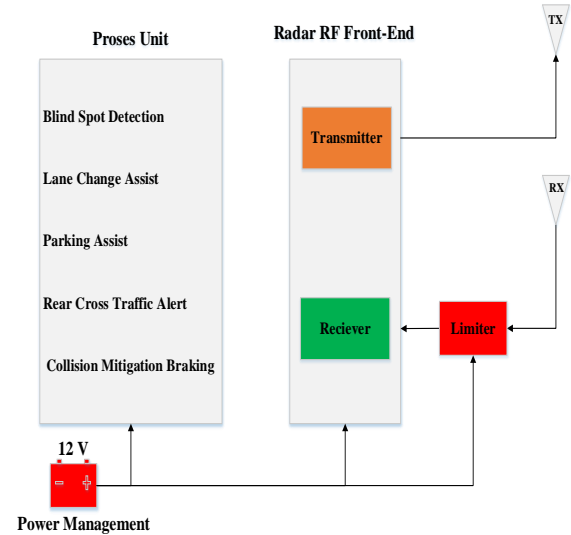

Figure 1. System block diagram showing limiter integration in automotive radar architecture.

At the core of the design lies a modified WR-42 waveguide structure with 10.668×4.318 mm cross-sectional dimensions, chosen for TE_{11} mode propagation at 24 GHz. The 60-mm long waveguide houses a Bourns 2045-23-BLF GDT module (8×6 mm) precisely centered to maximize electric field coupling, as illustrated in Figures 2,3,4. Its internal dimensions are given in reference [14]. This positioning ensures the GDT intercepts the maximum field intensity in the waveguide's dominant mode, with the aluminum oxide (Al_2O_3) GDT body (ε_r=9.4) requiring dielectric matching to the surrounding air-filled waveguide.

A standard K-band waveguide was used to design the 24 GHz limiter, and the dimensions considered for the aperture and internal dimensions of the GDT are given in Table 1.

Table 1. The size of the design parameters of the limiter (mm).

a	b	c	d	e	f	g	x	y	z
4.5	5	6	8	0.6	3.6	6	10.67	4.32	60

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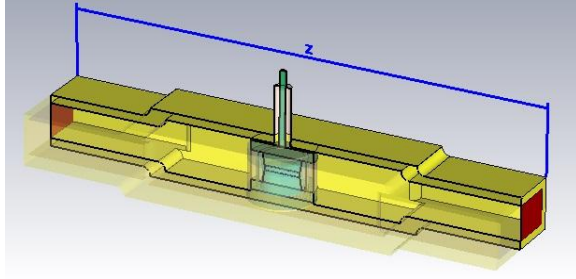
Figure 2. Side view of the designed discharger, which also shows the general view and the placement of the GDT
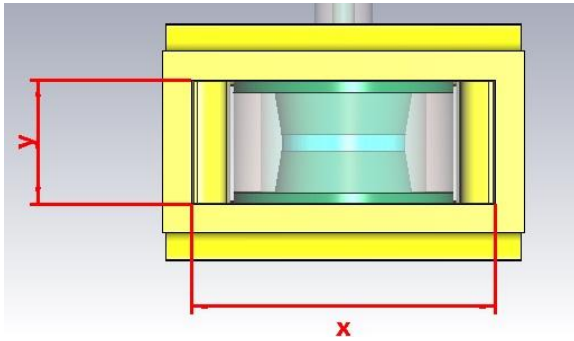

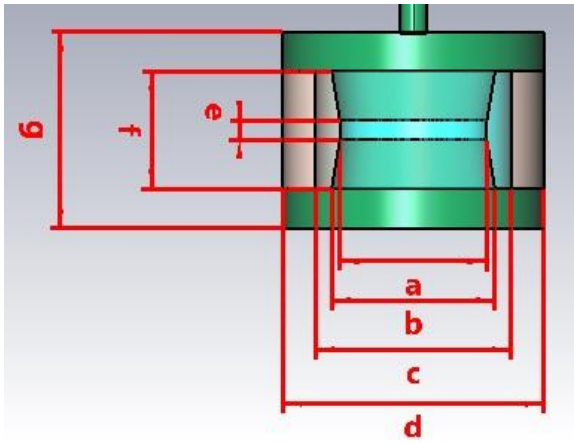**Figure 3. Front view ports dimensions and the placement of GDT**

Figure 4. Internal dimensions of GDT

The matching challenge was resolved through filling the waveguide with Rogers RO3035 material (ε_r=3.6, tanδ=0.0015), which provides an optimal compromise between impedance matching and loss characteristics.

This configuration yielded exceptional scattering parameters: S_{21}=-0.9 dB for insertion loss and S_{11}=-15.7 dB for return loss in normal mode operation of the discharger, as captured in the simulation results of Figure 5. Further refinement by adding iris structures adjacent to the GDT improved the impedance matching to S_{11}=-21.5 dB while maintaining the low insertion loss.

The plasma formation mechanism relies on precise control of several physical phenomena. When the incident field exceeds 100 V/m (E_b), the pre-ionized neon gas (75 Torr pressure) undergoes complete ionization, reaching an electron density of n_e=2.87$\times$10^{20} cm^{-3} calculated through the plasma frequency equation:

$$\omega_{P_e} = \left(\frac{e^2 * n_e}{\varepsilon_0 * m_e} \right)^{1/2} (Hz) \qquad (1)$$

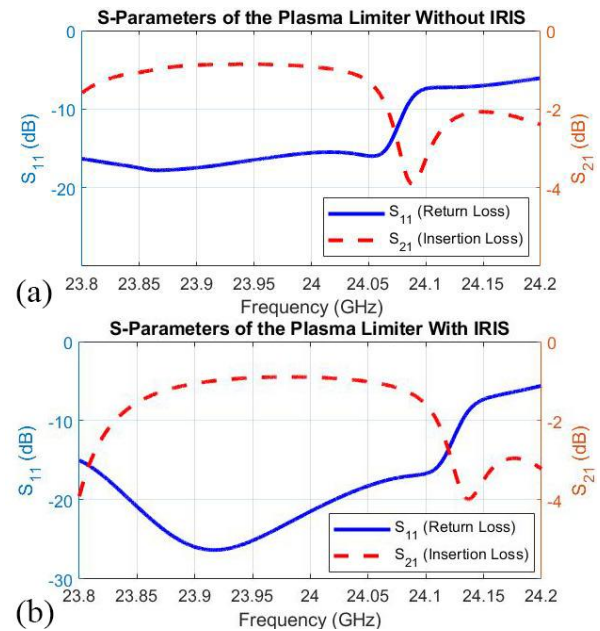$$n_{0_e} = \left(\frac{4 * \pi^2 * m_e * \varepsilon_0}{e^2} \right) * f_{p_e}^2 (cm^{-3})$$

(a)

(b)

Figure 5. S-parameter simulation results for (a) without, and (b) with matching iris.

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This corresponds to a Debye length $\lambda_D = 4.08 * 10^{-9}(cm)$, derived from:

$$\lambda_D = \sqrt{\left(\frac{\varepsilon_0 k T_e}{e^2 n_e}\right)}(cm) \qquad (2)$$

where T_e=1 eV (11,604 K) represents the electron temperature. The resultant plasma skin depth is $\delta = 3.14 * 10^{-4}(cm)$ ensuring effective reflection of incident waves.

The plasma limiter's operation hinges on a gas-filled cavity(e.g., argon, neon, helium, or a mixture of these) ionized by DC or RF sources. Under normal operation, low electron density permits minimal insertion loss. When power is exceeded from the threshold, plasma transitions to a metallic state, reflecting harmful signals [19, 20].

The dynamic response was modeled using the Drude dispersion model with ε_∞=1.0 and collision frequency ν_c=2.4×10^{10} s^{-1}. Figure 6 shows the simulated plasma frequency versus electric field characteristics, demonstrating the hysteresis between breakdown (E_b=100 V/m) and maintenance (E_m=50 V/m) thresholds. This behavior ensures stable plasma persistence during transient interference while allowing automatic recovery when the threat subsides.
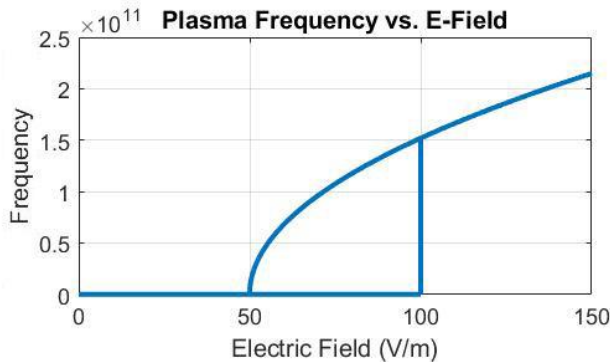

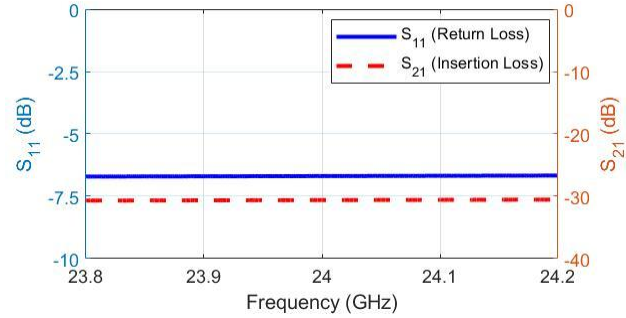**Figure 6. Plasma frequency vs. electric field intensity.**

Figure 7. S-parameters during high-power limiting

High-power simulations revealed the limiter's protective capability, with S_{21} plunging to -30.6 dB during plasma conduction (Figure 7). The complete performance comparison between operational states is presented in Table 2.

The use of standard GDT technology ensures cost-effectiveness, with the Bourns 2045 module offering proven reliability across the automotive temperature range (-40°C to +125°C).

Table 2. Performance comparison between operational modes

Parameter	Low-Power	High-Power
S11	-21.5 dB	-6.7 dB
S21	-0.9 dB	-30.6 dB

The specified gas discharge tube (2045-23-BLF) exhibits a plasma formation voltage threshold of 230 V. This characteristic enables plasma generation through DC voltage application alone (without requiring auxiliary electromagnetic wave excitation), thereby establishing an effective barrier against electromagnetic wave propagation.

A key innovation of our limiter design lies in its field-programmable protection capability, allowing end-users to customize the system's protection threshold according to specific power handling requirements. This is achieved through

a voltage multiplier circuit that boosts the standard 12V automotive supply to the desired operational voltage (230V). The implementation benefits from vehicular electrical systems' inherent high-current capacity (50-100 A), ensuring stable power delivery without battery performance degradation, On-demand plasma activation independent of incident RF power levels, and adjustable protection thresholds for different radar architectures. This approach represents a significant advancement over conventional fixed-threshold limiters by introducing programmable protection while maintaining compatibility with standard vehicle electrical systems.

3. Conclusion

This study presented the design and optimization of a plasma-based power limiter for 24 GHz automotive radar systems, focusing on enhanced EMI suppression. The proposed limiter, utilizing a GDT within a K-band waveguide filled with Rogers RO3035 dielectric, demonstrated exceptional performance metrics. Under normal operation, it achieved a low insertion loss (0.9 dB) and favorable return loss (15.7 dB), while providing strong isolation (>30 dB) against high-power microwave (HPM) threats with a rapid sub-100 ns response time. The plasma limiter's passive nature, self-recovery, and tolerance to extreme temperatures (-40°C to +125°C) make it ideal for automotive applications. Its tunability addresses a critical gap in existing high-power limiter designs.

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