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AlGaN/GaN HEMT X-Band Frequency Doublers with Novel Fundamental Frequency Reflector Scheme

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SUMMARY The first implementations of X-band AlGaN/GaN HEMT single-ended frequency doublers are presented in this paper. Two types of fundamental frequency signal reflector schemes have been demonstrated for the frequency doubler application. Open-circuited quarter-wavelength microstrip line at the fundamental frequency is utilized for the reflector in a conventional way. In the other architecture a printed antenna is employed as a radiator as well as a novel fundamental frequency reflector. A microstrip rectangular patch antenna operating at the second harmonic frequency of the doubler was designed and integrated with AlGaN/GaN HEMT based on active integrated antenna design concept. Using AlGaN/GaN HEMT with 1 mm gate periphery, two 4 to 8 GHz frequency doublers were designed by the described design methodologies, fabricated, and tested. For the conventional frequency doubler, a conversion gain of 0.6 dB and with an output power of 15 dBm was observed. A conversion gain of 5 dB and an output power of 25 dBm with embedded antenna gain were achieved at a drain voltage of 12 V for the doubler integrated with the patch antenna.

key words: *frequency doubler, AlGaN/GaN HEMT, active integrated antenna, conversion gain*

1. Introduction

In microwave and millimeter-wave communication and radar systems, RF signal sources with low phase noise, good frequency stability, and high output power performance are required. Frequency multipliers in conjunction with low frequency oscillators have widely been used for satisfying those requirements because it allows better overall phase noise performance [1]. Nonlinear devices such as FETs, BJTs, or HEMTs have been utilized for active multipliers while Schottky diode or p-n junction varactors for passive multipliers. Either single-ended or balanced architectures are typically used for frequency multiplier design. Single-ended structures provide low cost and narrow bandwidth characteristics in a simple design, but poor performance. In contrast, balanced type multipliers with input or output balun offers broader bandwidth and higher output power than single-ended [2]–[6].

Recently, there has been great interest in developing wide band-gap semiconductor devices such as GaN-based HEMTs for high power circuit applications at microwave and millimeter-wave frequencies. This is generally due to their high breakdown voltage, high current density, and fast carrier transport characteristics. Besides the high power generation capability, their superior thermal properties have been extended up to 750°C, extremely high operating temperature [7]. In such extreme conditions, relying on commonly used GaAs-based HEMTs becomes impractical. This may result in popularity of the GaN-based HEMTs in high power and high temperature applications. With maturity in the AlGaN/GaN HEMT device technologies, high performance amplifier and oscillator circuits have been demonstrated and reported [8]–[10]. Furthermore, Chung et al. demonstrated antenna-integrated AlGaN/GaN HEMT power amplifier for the next generation high efficiency RF front-end applications based on the active integrated antenna (AIA) design approach. A maximum PAE of 55% and output power of 30 dBm were reported at 2.45 GHz [11].

The AIA design approach has been extensively employed in advanced RF front-end applications [11]–[13]. In this design concept, RF transmitting/receiving circuitry and antenna are designed as a whole entity and integrated without assumption of 50 Ω interface between the circuit and the antenna. One of the attractive features of the AIA is that the antenna is serving as both an output load and a radiator over a certain frequency range, as well as providing circuit functions such as signal filtering and frequency tuning. This results in a functional compact design and eliminates the effect of any cable and feedline losses.

In this paper, different types of fundamental signal reflectors at output matching circuit have been investigated. AIA design concept was applied to design of frequency doubler. AlGaN/GaN HEMT device technologies is presented in Sect. 2 followed by design of the frequency doublers utilizing a microstrip transmission line and a microstrip patch antenna based on the AIA design approach in Sects. 3.1 and 3.2, respectively. Experimental measurement results and discussion is presented in Sect. 4 for both of the frequency doublers.

2. AlGaN/GaN HEMT Technology

The AlGaN/GaN HEMT epitaxial layer was grown by metallic organic chemical vapor deposition (MOCVD).

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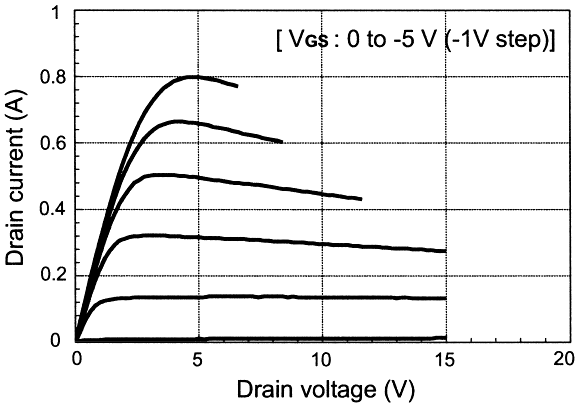

Fig. 1 DC *I-V* characteristics of the 1 mm-wide AlGaN/GaN HEMT.

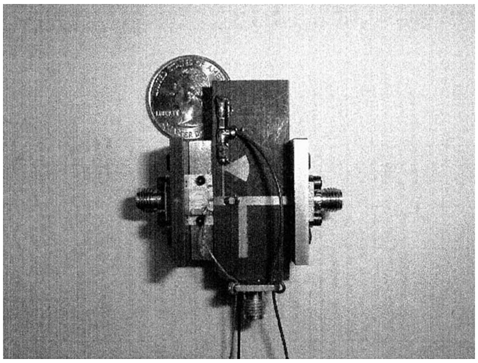

Fig. 2 Photograph of AlGaN/GaN HEMT frequency doubler with $\lambda/4$ open-circuited microstrip line.

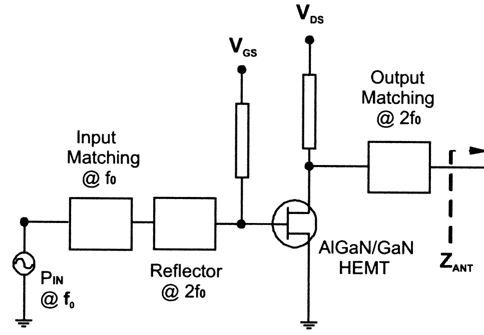

Fig. 3 Architecture of frequency doubler using the AIA design concept.

The layer consists of 200 Å $Al_{0.3}Ga_{0.7}N$ doped cap layer followed by 30 Å $Al_{0.3}Ga_{0.7}N$ undoped layer, 500 Å GaN undoped layer, and 1.2 μm GaN buffer layers grown on semi-insulating SiC substrate. AlGaN/GaN HEMT was fabricated through device isolation, ohmic metallization, gate metallization, Si_3N_4 passivation, and air-bridge processes. Ohmic metallization was formed by Ti/Al/Ni/Au followed by 900°C and 40 second rapid thermal annealing. This yields typically resistance of 0.4 Ω-mm [14]. As^+ and He^+ were utilized for ion implantation device isolation and Pd/Au bilayer metal was used for gate metal contact. For the 1 mm-wide AlGaN/GaN HEMT, a saturated drain current (I_{DSS}) of about 800 mA and 40 V drain to gate breakdown voltage was observed. Figure 1 shows the measured DC *I-V* characteristics for the 1 mm-wide HEMT.

3. Design and Fabrication of AlGaN/GaN HEMT Frequency Doublers

3.1 Frequency Doubler Using $\lambda/4$ Microstrip Line Reflector

The fundamental frequency has to be well suppressed at the output matching network side of the circuit. This is done using either a fundamental frequency signal reflector for the single-ended or signal cancellation with 180° phase difference used in balanced structure. In the single-ended frequency doubler structure, a $\lambda/4$ open-circuited stub (at the fundamental frequency) is simply employed as the reflector. Thus, in this frequency doubler scheme, the $\lambda/4$ wavelength transmission line was used as the 4 GHz fundamental frequency signal reflector at output matching circuit which was designed at the second harmonic frequency of 8 GHz.

In the input matching network, the second harmonic reflector using a $\lambda/4$ open-circuited stub (at 8 GHz) was employed with input matching network designed at 4 GHz to improve conversion gain performance [4], [5].

The design of the frequency doubler utilizing an AlGaN/GaN HEMT with gate width of 1 mm and gate length of 0.8 μm was done based on measured small-signal S-parameters. The bias voltage, $V_{DS} = 12$ V and $I_{DS} = 70$ mA, was set for the measurement. The DC bias was chosen such that the device was operating at similar bias condition when large RF input power was applied to frequency doubler with initial device pinch-off DC bias condition for obtaining higher 2nd harmonic power. The input matching network was fabricated on Alumina with dielectric constant of 9.8 and thickness of 0.381 mm. The output matching circuit was built on 0.787 mm-thick Duroid substrate with dielectric constant of 2.33. The fabricated matching networks were combined with the AlGaN/GaN HEMT using Au bonding wire. The fabricated frequency doubler was mounted on a brass test fixture for heat sinking as shown in Fig. 2.

3.2 Frequency Doubler Using Active Integrated Antenna Design Concept

The AIA design concept is applied to design a frequency doubler. In this approach, as shown in Fig. 3, the antenna is employed as an output radiator as well as a new type of a fundamental frequency signal reflector.

The circuit schematic is basically realized by designing an antenna at a resonant frequency corresponding to the second harmonic and integrating an active device with the antenna. Thus, the antenna as an output load in the circuit radiates the second harmonic generated by the active device in the strong nonlinear operation. However, for the fundamental frequency signal, it reactively terminates the device so that the fundamental frequency signal power is efficiently suppressed by the antenna itself without an additional fundamental frequency signal reflector. As a result, the antenna operates as an equivalent fundamental frequency reflector in the conventional frequency doubler. This eliminates the necessity of a fundamental frequency reflector in the conventional frequency doubler. It provides additional advantage such that the cable and feedline losses are minimized when an external antenna is connected by employing the AIA concept as well.

In this work, the single-ended AlGaN/GaN HEMT frequency doubler AIA consisted of 1 mm-wide AlGaN/GaN HEMT and a microstrip rectangular patch antenna as an output radiator. The passive patch antenna was designed at resonant frequency of 8 GHz and printed on Duroid substrate with dielectric constant of 2.33 and thickness of 0.787 mm. Then, the measured antenna impedance (Z_{ANT}) was embedded into an Agilent ADS simulation as the final output port instead of a conventional 50 Ω load. The output matching network transformed output impedance of the HEMT to the conjugate of Z_{ANT} based on the AIA design concept. In the input matching network, the 8 GHz second harmonic reflector using a $\lambda/4$ open-circuited stub was used in the input matching network designed at the fundamental frequency of 4 GHz. The designed input matching network was fabricated on the same substrate as that of the circuit discussed in Sect. 3.1. The entire output matching network including the patch antenna was built on the same substrate used for the passive antenna. The fabricated matching networks were combined with the AlGaN/GaN HEMT using an Au bonding wire and mounted on a test fixture. Figure 4 shows the photograph of the fabricated the antenna-integrated AlGaN/GaN HEMT frequency doubler.

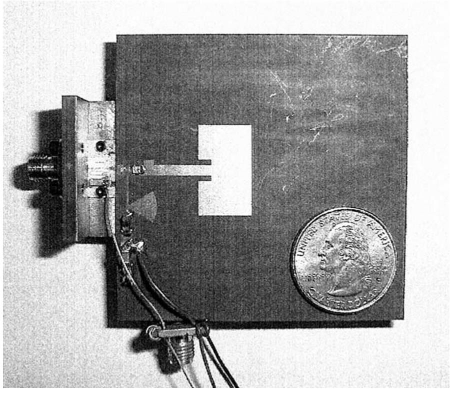

Fig. 4 Photograph of AlGaN/GaN HEMT frequency doubler integrated with a rectangular patch antenna.

4. Measured Results and Discussion

4.1 Frequency Doubler Using $\lambda/4$ Microstrip Line Reflector

The bias voltage, $V_{DS} = 12$ V and $I_{DS} = 70$ mA, was set for testing small-signal input return loss characteristic of the frequency doubler using HP8510C network analyzer. Over a frequency range from 3.9 GHz to 4.2 GHz input return loss less than −10 dB was observed. For large-signal measurements, $V_{DS} = 12$ V and $V_{GS} = -5$ V DC bias voltages which corresponds to device pinch-off operating region were applied. The measured conversion gain and output power at the second harmonic frequency with respect to the input power are shown in Fig. 5.

A maximum conversion gain of 0.17 dB at 8 dBm input power and saturated output power of 15.34 dBm were observed. Figure 6 shows the conversion gain characteristics versus frequency measured from 3.7 to

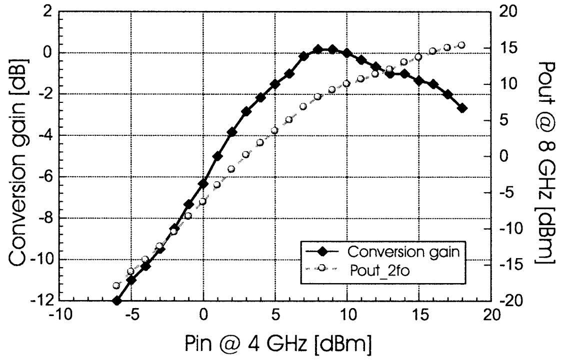

Fig. 5 Measured conversion gain and output power with respect to the input power for the conventional AlGaN/GaN HEMT frequency doubler.

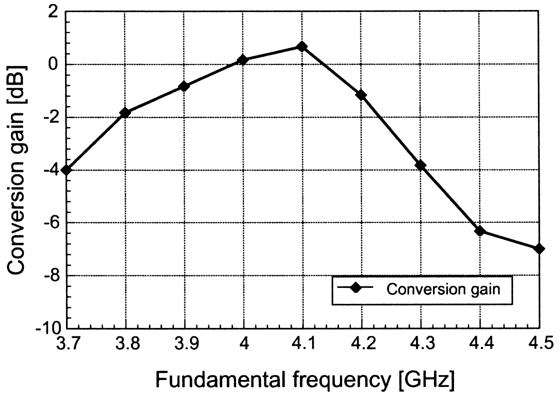

Fig. 6 Measured conversion gain as a function of frequency for the conventional AlGaN/GaN HEMT frequency doubler.

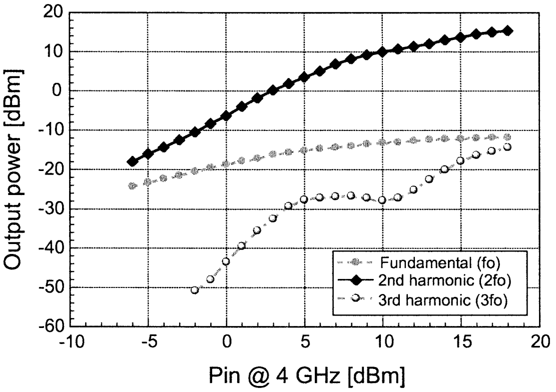

Fig. 7 Measured output power at fundamental, the 2nd, and 3rd harmonics for the conventional AlGaN/GaN HEMT frequency doubler.

4.5 GHz. A conversion gain of up to 0.67 dB was achieved over the measured frequency range. The measured suppression characteristic of the fundamental and 3rd harmonic frequencies is shown in Fig. 7. Suppression of 27 dBc and 30 dBc for the fundamental and 3rd harmonic frequencies, respectively, was observed.

4.2 Frequency Doubler Integrated with a Microstrip Rectangular Patch Antenna

Measurements for the antenna-integrated frequency doubler structure were done in an anechoic chamber based upon the Friis transmission Eq. (1) [11]–[13], [15].

$$P_{rec} = (1 - |\Gamma_{trans}|^2) G_t \frac{P_{in}}{4\pi R^2} \cdot (1 - |\Gamma_{rec}|^2) \frac{\lambda^2}{4\pi} G_r \qquad (1)$$

In Eq. (1), P_{rec} and P_{in} are received power and input power delivered to the radiator, patch antenna, from the AlGaN/GaN HEMT. Γ_{trans} and Γ_{rec} are reflection coefficients of transmitting and receiving side, respectively. G_t and G_r are transmitting and receiving antenna gains and $1/4\pi R^2$ presents free space loss.

To test the large-signal performance of the frequency doubler integrated with a patch antenna, the bias voltages were set to V_{DS} of 12 V and V_{GS} of −5 V same as that of the conventional circuit. A frequency synthesizer with 4 GHz fundamental frequency was used for the RF source. Equation (1) allows us to get output performance at the end of the frequency doubler after de-embedding the receiving antenna gain and free space loss. The measured conversion gain and output power at the second harmonic frequency with respect to the input power are shown in Fig. 8. Note that the output power is defined at the end of the frequency doubler. It embeds antenna gain with taking into account cable loss. A maximum conversion gain of 5 dB at an input power level of 14 dBm and saturated output power of 25 dBm are obtained.

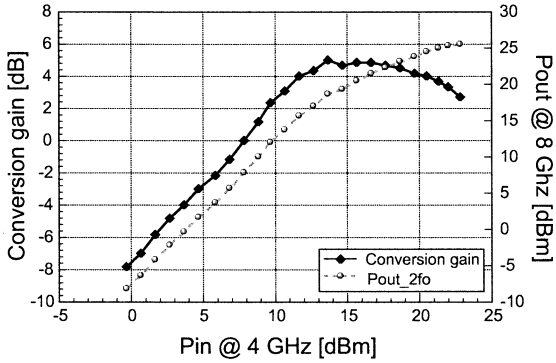

Fig. 8 Measured output power and conversion gain for the AlGaN/GaN HEMT frequency doubler integrated with a patch antenna.

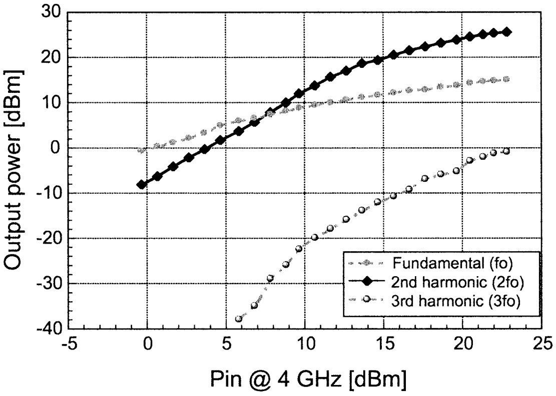

Fig. 9 Measured output power at fundamental, the 2nd, and 3rd harmonics for the AlGaN/GaN HEMT frequency doubler integrated with a patch antenna.

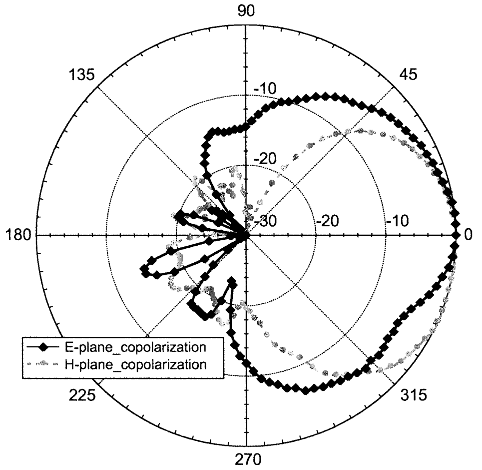

Fig. 10 Measured E- and H-plane radiation patterns for the AlGaN/GaN HEMT frequency doubler integrated with a patch antenna at 8 GHz.

In Fig. 9, measured suppression characteristics of fundamental frequency and the 3rd harmonic at the output of the AlGaN/GaN HEMT frequency doubler integrated with the rectangular patch antenna is shown.

The suppression is better than 10 dB and 25 dB for the fundamental and the 3rd harmonic frequencies, respectively. As input power level increases, the HEMT device is operating at a stronger nonlinear region so that the 2nd harmonic output power level is increasing following increase of input power but fundamental signal power is efficiently suppressing by the patch antenna.

E- and H-plane radiation patterns for the antenna integrated AlGaN/GaN HEMT frequency doubler with 4 GHz input frequency were measured at 8 GHz. For the radiation pattern measurements, the input power level was set to 15 dBm at which peak conversion gain was observed. Note that the radiation power is normalized to 0 dB and shown in Fig. 10.

5. Conclusion

Two 4 to 8 GHz single-ended AlGaN/GaN HEMT frequency doublers have first been demonstrated. $\lambda/4$ open-circuited microstrip line was conventionally used for the fundamental signal reflector. AIA design concept was applied to design of a frequency doubler. An antenna operates as an output radiator as well as an efficient fundamental frequency reflector. By employing the AIA design approach, a compact design was accomplished and cable and feedline loss was also eliminated.

The saturated output power of 15.34 dBm and maximum conversion gain of 0.17 dB were achieved from the frequency doubler with a 1 mm-wide AlGaN/GaN HEMT using $\lambda/4$ open-circuited microstrip line. For the antenna-integrated frequency doubler, a saturated output power of 25 dBm and maximum conversion gain of 5 dB with embedded antenna gain were achieved for the frequency doubler AIA.

From the measured data, it is demonstrated that AlGaN/GaN HEMTs can be used as frequency doublers with high output power and good conversion gain. The AIA design concept can also be successfully applied to design of frequency multiplier structures as well as amplifiers. An antenna operates as a new type of fundamental frequency signal reflector so that fundamental frequency signal was efficiently suppressed.

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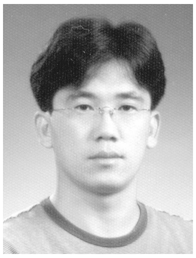

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