Abstract — This paper presents a new architecture for an AlGaN/GaN HEMT frequency doubler using the active integrated antenna design approach. A microstrip patch antenna designed at the second harmonic is integrated with the HEMT. The antenna operates as a fundamental frequency reflector in this circuit. Using AlGaN/GaN with 1mm gate periphery, a 4 - 8 GHz frequency doubler was designed by the suggested design methodology, fabricated, and tested. For the AlGaN/GaN HEMT frequency doubler integrated with the patch antenna, conversion gain of 5 dB and output power of 25 dBm were achieved in pinch-off region with a drain voltage of 12 V.

Key words: AlGaN/GaN, HEMT, Frequency Doubler, Conversion Gain

II. New Architecture for Frequency Doubler

Conventional frequency doublers have typically been designed at the second harmonic for the output matching and at the fundamental frequency for the input matching network. The fundamental frequency is suppressed at the output matching network side using a λ/4 open circuited stub (at the fundamental frequency) as the reflector [1] [4]. In the suggested new architecture, a frequency doubler is designed based on the AIA design approach. This circuit schematic is realized by designing an antenna at a resonant frequency corresponding to the second harmonic and integrating an active device with the antenna. Therefore, the antenna as an output load in the circuit radiates the second harmonic generated by the active device in the strong nonlinear operation while efficiently suppressing the fundamental frequency signal power. 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. In addition, the cable and feedline losses are minimized when an external antenna is connected by employing the AIA concept. As shown in Fig. 1, the single-ended AlGaN/GaN HEMT frequency doubler consists of AlGaN/GaN HEMT and a microstrip rectangular patch antenna. The antenna was designed at the second harmonic frequency of 8 GHz and output matching network transforms output impedance of the HEMT to the conjugate of antenna impedance (ZANT) based on the AIA design concept.
In the input matching network, the second harmonic reflector using a $\lambda/4$ open circuited stub (at the second harmonic) was employed with input matching network designed at the fundamental frequency of 4 GHz [1] [4].

III. AlGaN/GaN HEMT Frequency Doubler integrated with a Rectangular Patch Antenna

The AlGaN/GaN HEMT epitaxial layer was grown by metallic organic chemical vapor deposition (MOCVD). 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 SiC substrate. AlGaN/GaN HEMT was fabricated through device isolation, ohmic metallization, gate metallization, Si$_3$N$_4$ passivation, and air-bridge processes.

As the output radiator, a rectangular patch antenna was used with a microstrip feedline. The antenna was designed and fabricated on Duroid substrate with dielectric constant of 2.33 and thickness of 31 mils at the resonant frequency of 8 GHz. The measured $Z_{\text{ANT}}$ was embedded to an Agilent ADS simulation as the final output port instead of a conventional 50 Ω load.

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 input matching network was fabricated on Alumina with dielectric constant of 9.8 and thickness of 15 mils. The output matching network with the antenna was built on the same substrate used for the passive antenna. The fabricated matching networks were combined with the AlGaN/GaN HEMT using Au bonding wire. The fabricated frequency doubler was mounted on a metal fixture for heat sinking. The photograph of the fabricated antenna integrated AlGaN/GaN HEMT frequency doubler is shown in Fig. 2.

IV. Measurement Results and Discussion

Measurements were done in an anechoic chamber based upon the Friis transmission equation (1) [5-6] [9].

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

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

To test the performance of the antenna integrated with the AlGaN/GaN HEMT frequency doubler, the bias voltages were set to $V_{\text{ds}}$ of 12 V and $V_{\text{gs}}$ of -5 V, corresponding to the pinch-off region rich in even harmonics. A frequency synthesizer with 4 GHz fundamental frequency was used for the RF source. The above 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. 3. 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 $P_{\text{out}}$ of 25 dBm are obtained. In Fig. 4, the 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.

In addition, the 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. Note that the radiation power is normalized to 0 dB and shown in Fig. 5.

Fig. 3 Measured output power (P_{out}) and conversion gain for the AlGaN/GaN frequency doubler integrated with the rectangular patch antenna

V. Conclusion

A new architecture for frequency doubler based on the AIA design concept has been presented. A microstrip rectangular patch antenna was integrated with AlGaNSiH HEMT for the new frequency doubler. In this structure, the second harmonic signal radiates through the output antenna while the fundamental signal does not. This structure eliminates the necessity of a separate reflector for the fundamental frequency at the output of a conventional frequency doubler. The saturated P_{out} of 25 dBm and maximum conversion gain of 5 dB were achieved from the antenna integrated frequency doubler using an AlGaN/GaN HEMT with 1mm gate periphery. 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 employed to frequency multiplier structures as well as amplifiers.

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