Third-Harmonic Frequency Multiplication of a Two-Stage Tapered Gyrotron Traveling-Wave Tube Amplifier

C. W. Baik, S. G. Jeon, D. H. Kim, N. Sato, K. Yokoo, and G. S. Park, Member, IEEE

Abstract—The frequency multiplication of a two-stage tapered gyrotron traveling-wave tube amplifier is experimentally verified in low-voltage and low-current operation. By modulating an axis-encircling electron beam at the fundamental-harmonic cyclotron frequency in the input stage, a frequency-tripled signal induced by the third-harmonic component of the modulated beam current is chosen to be extracted from the output stage. Both interaction stages are linearly tapered to improve stability and bandwidth. The third-harmonic frequency multiplication is predicted theoretically and investigated using a self-consistent large-signal theory and a particle-in-cell code simulation, which estimate a pure third-harmonic generation and a power-scaling law. In the experiment, X-band drive signals from 10.6 to 12 GHz are multiplied by a factor of three to produce Ka-band output frequencies from 31.8 to 36 GHz, showing reasonable agreement with theoretical predictions for a 30-kV, 160-mA axis-encircling electron beam.

Index Terms—Frequency multiplication, gyrotron, gyrotron traveling-wave tube, harmonic frequency.

I. INTRODUCTION

To date, the promising potential of gyrotron traveling-wave tube (gyro-TWT) amplifiers as coherent high-power millimeter-wave sources has elicited great interest in the realization of applications such as high-resolution radars, electronic warfare, and broadband high-density communications [1]-[3]. Together with the advantages of conventional traveling-wave tubes and gyrotrons [4], gyro-TWTS have demonstrated high gain and high-power capability with increased bandwidth [5], [6]. However, for many years, there has been a major obstacle in achieving stable output power with reasonable bandwidth due to spurious oscillations [5]-[8]. These unwanted oscillations include the absolute instability at the cutoff frequency, reflective oscillations from the output mismatch, and backward wave oscillations [9]. In low-voltage operation below 100 kV, the elimination of the absolute instability near the cutoff frequency has been a matter of concern [10]. To overcome this problem, a distributed interaction circuit of a severed and tapered two-stage waveguide was introduced and researchers demonstrated stable amplification with a 20% bandwidth and a saturated gain of 25 dB at a beam voltage of 30 kV [11]. By tapering the interaction circuit, the distributed interaction through the frequency-dependent wave cutoff in different positions with effectively reduced interaction length improved the bandwidth and the stability from spurious oscillations in low-voltage operation [11], [12].

Additional significant issues include harmonic operation. In contrast to conventional linear beam devices, a multitude of cyclotron harmonics generates a number of harmonic oscillations in gyro-devices [13]. Therefore, the electron cyclotron harmonic operation by the proper choice of a TE-mode and a harmonic number has been an attractive solution to meet the demand for high-frequency amplifiers alleviating the drive frequency and magnetic field requirement [14]-[17]. Furthermore, the mechanism of frequency multiplication is of considerable theoretical interest due to its inherent nonlinear and multimodal nature [18]. Such a splendid feature of harmonic frequency-multiplying operation, achieving both frequency multiplication and power amplification, has been realized in gyrokystrons and gyro-TWTS [13], [15], [19]. However, the need still exists for an experimental demonstration of higher-harmonic frequency multiplication in gyro-TWTS with improved stability and bandwidth.

The objective of this work is to verify the frequency multiplication by the third-harmonic interaction of electron cyclotron mode and to develop a stable frequency-multiplying and power-amplifying gyro-TWT with improved bandwidth in low-voltage operation of 30 kV. To achieve this goal, a two-stage tapered rectangular waveguide is employed as an interaction circuit [11], [20]. Here, the fundamental harmonic interaction by an X-band drive signal in the input stage modulates the electron beam to have a number of cyclotron harmonic frequencies by the ballistic bunching process [21], then the selected and amplified third harmonic radiation at the Ka-band frequency is extracted from the output stage. Therefore, the drive frequency as well as the required magnetic field is effectively reduced by a factor of three because of the third-harmonic interaction. To remove unwanted oscillations from higher order modes and to simplify the coupling structure, the fundamental TE$_{10}$ mode is chosen in both stages. For a strong interaction and beam transmission, an axis-encircling electron beam of 30 kV from a cusp gun is utilized [22], [23].

This paper presents the theoretical design of the third-harmonic frequency-multiplying gyro-TWT amplifier and associated experimental results. In addition, we describe a study of the interesting physical characteristics of electron cyclotron...
harmonic multiplication by using a self-consistent large-signal theory and a particle-in-cell simulation [24], [25]. This paper is organized as follows. Section II is an overview of the experimental design and setup with the measured properties of a magnetic field and a directional coupler. In Section III, the theoretical prediction of the performance of the presented interaction circuit is discussed in detail. The measured characteristics of the two-stage tapered gyro-TWT in Section IV are followed by concluding remarks in Section V.

II. EXPERIMENTAL DESIGN, SETUP, AND RESULTS

The dispersion relation of the proposed third-harmonic frequency-multiplying gyro-TWT amplifier is shown in Fig. 1. In the input stage, the fundamental harmonic interaction is denoted by the electron cyclotron resonance between the waveguide mode and the first harmonic beam mode at X-band frequencies. The third-harmonic interaction in the output stage is achieved by increasing the cutoff frequency of the waveguide mode by a factor of three to match the third-harmonic beam mode. Within the tapered waveguide-type interaction circuit, the cutoff frequency in each stage changes along the axial position. Thus, operating frequencies due to the electron cyclotron resonance also vary from $\omega_1$ to $\omega_2$ in the input stage, and from $3\omega_1$ to $3\omega_2$ in the output stage. To maintain the cyclotron resonance condition along the tapered circuit, a tapered external magnetic field is also required.

Figure 2 presents the layout of the experimental setup for the third-harmonic frequency-multiplying two-stage tapered gyro-TWT amplifier. There are three main parts: an electron gun, electromagnets for the tapered magnetic field, and an interaction circuit. A Pierce-type cusp electron gun for a 30-kV electron beam is employed with three air-cooled gun magnets and an iron pole piece which forms a cusp magnetic field for the generation of an axis-encircling electron beam. To build up the tapered magnetic field in the interaction region, three water-cooled solenoidal electromagnets with 13 sub magnets enclosed by thick pure iron are designed using POISSON/SUPERFISH code [26] and manufactured, producing a field of up to 5 kG. This is a sufficient magnetic field strength for the generation of Ka-band signals due to the harmonic operation. It corresponds to one-third of the required magnetic field of 15 kG when fundamental-harmonic operation is considered.

Detailed design parameters of the gyro-TWT amplifier are given in Table 1.

Since the external axial magnetic field profile controls the condition of the electron beam, there are two significant considerations: first, the magnetic field in the gun region determines the production of a high-quality electron beam with a low-velocity spread and a high beam velocity ratio $\alpha = v_t/v_z$, where $v_t$ is the perpendicular velocity of the electron beam [23]. Second, the bidirectionally tapered mag-

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>DESIGN PARAMETERS OF THE THIRD-HARMONIC FREQUENCY-MULTIPLYING GYRO-TWT AMPLIFIER.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam voltage</td>
<td>30 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>1 A</td>
</tr>
<tr>
<td>Beam velocity ratio $\alpha = v_t/v_z$</td>
<td>1.6</td>
</tr>
<tr>
<td>Duty</td>
<td>12 $\mu$s, 20 Hz</td>
</tr>
<tr>
<td>Input stage harmonic number</td>
<td>1</td>
</tr>
<tr>
<td>Output stage harmonic number</td>
<td>3</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>3.8 $\sim$ 4.5 kG</td>
</tr>
<tr>
<td>Input stage cutoff frequency</td>
<td>10.3 $\sim$ 12 GHz</td>
</tr>
<tr>
<td>Output stage cutoff frequency</td>
<td>31.0 $\sim$ 36.0 GHz (Taper-I)</td>
</tr>
<tr>
<td>Operating mode</td>
<td>TE\textsubscript{10}</td>
</tr>
<tr>
<td>Guiding center radius</td>
<td>0.0 mm</td>
</tr>
<tr>
<td>Larmor radius</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Input stage length</td>
<td>0.08 m</td>
</tr>
<tr>
<td>Sever length</td>
<td>0.02 m</td>
</tr>
<tr>
<td>Output stage length</td>
<td>0.3 m</td>
</tr>
<tr>
<td>RF input power</td>
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</tr>
</tbody>
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netic field in the interaction region directly affects the electron cyclotron resonance condition. Thus, the magnetic field profile determines the device performance. The theoretical design profile and the measured magnetic field are depicted in Fig. 3. A good agreement is shown near the electron gun region; however, about 1% difference at the highest tapered magnetic field is measured; therefore, computer-based control of all the magnets is required for precise readjustment.

For an injection of X-band drive signals into the input stage, a coupling structure is required. A designed 0-dB directional coupler with an interaction circuit is illustrated in Fig. 4. A picture of the fabricated 0-dB 15 hole directional coupler, corresponding to the front part of the cutaway view of Fig. 4, is shown in Fig. 5. Bethe’s coupling theory and 6-element 4-array 2-row Chevyshev polynomials are applied to achieve 0-dB coupling and high directivity over the band [27]. The design is confirmed by simulations using the Ansoft High Frequency Structure Simulator (HFSS). The measurement also shows a flat coupling of 0.5 dB and a directivity greater than 20 dB as depicted in Fig. 6.

III. THEORETICAL ANALYSIS

In this Section, theoretical predictions of particular characteristics of the third-harmonic frequency-multiplying gyro-TWT, using a two-and-half dimensional particle-in-cell code MAGIC2D as well as a self-consistent large-signal theory, are described [24], [25]. First, the analysis of simulation results on the beam bunch from MAGIC2D is discussed. Device performance comparison between the large-signal theory and the MAGIC2D simulation is also presented.

A. Electron Bunch

Figure 7 is the configuration of the interaction circuit for the particle-in-cell simulation with the phase plot of the electron beam bunch and the amplified electric field. In the Cartesian coordinate system of the MAGIC2D code, the ignored coordinate in Fig. 7(a) is the $y$-axis. Considering the rectangular
TE\textsubscript{01} mode in each stage, the direction of the electric field is the ignored coordinate \(y\). Therefore, the cutoff frequency is determined by the width of the waveguide in direction of \(x\). The waveguide width \(L_x\) is linearly tapered, and follows 
\[ L_{x,i} = L_{x,0,i} + a_i |z - z_0|, \]
where \(L_{x,0,i}\) is the width at the narrow end of the \(i\)th stage at the axial position \(z = z_0\) and \(a_i\) is the constant slope of the \(i\)th stage. Note that the ignored coordinate \(y\) has a normalization of 1 meter, so the power and the strength of the electric field need to be converted by a factor corresponding to the height in the structure. To generate an ideal axis-encircling electron beam, an artificial cathode at the left perimeter is considered. The input command ‘FREESPACE’ is also required to prevent RF reflections from the outer boundaries by absorbing all signals. The X-band input drive power is provided at the line of the input command ‘DRIVER’. After the fundamental-harmonic interaction in the input stage, the evolution of the electron bunch in the output stage appears as in Fig. 7(a) with the electric field amplified more than 10 times as depicted in Fig. 7(b). In addition, the guide wavelength in the input stage is reduced to about one-third in the output stage by the third-harmonic interaction.

The instantaneous electron bunch and simultaneous electric field are magnified as shown in Fig. 8 at the axial section of \(z = 0.25 \sim 0.45\) m. The position phase space of the electrons indicates that there are three bunches in the cross section of the \(xy\)-plane; however, a strong bunch with the wavelength \(\lambda_{beam}\) is followed by two successive and relatively weak bunches separated by the wavelength \(\lambda_{beam}^{(3)}\). The guide wavelength of the electric field by the third harmonic \(\lambda_g^{(3)}\) is approximately equal to \(\lambda_{beam}^{(3)}\). Therefore, the strong bunch is the initially modulated fundamental-harmonic bunch of electrons produced by a drive signal of 11.8 GHz, and other subsequent electron bunches are from the third-harmonic interaction at a Ka-band frequency of 35.4 GHz.

To investigate the third-harmonic effect on the electron bunch in detail, an artificial lossy material is introduced in the whole output stage. Then, there are no amplified Ka-band RF signals for the generation of the two successive weak electron bunches. In other words, the origin of those two weak bunches is thought to be the third-harmonic interaction in the output stage. Consequently, if there is no third-harmonic interaction of the Ka-band signal, only one strong electron bunch modulated by the X-band frequency is expected. This presumption is proven as shown in Fig. 9.
bunches in the momentum space is achieved by examining the cross section illustrated in Fig. 10. Figure 10(a) and (b) are given by the third-harmonic interaction at the axial sections of $z = 0.30 \sim 0.32$ m and $z = 0.38 \sim 0.40$ m, respectively, corresponding to cross sections of an axial width of 2 cm in Fig. 8. By excluding the third-harmonic interaction in the output stage, Fig. 10(c) and (d) are extracted from Fig. 9 at the axial sections of $z = 0.30 \sim 0.32$ m and $z = 0.38 \sim 0.40$ m, separately. Therefore, the electron bunch in the output stage of the third-harmonic frequency-multiplying gyro-TWT is the combination of a fundamental-harmonic bunch and two relatively weak bunches by the third harmonic interaction.

Fig. 10. Comparison of the shapes of electron bunches in cases: (a, b) the third-harmonic interaction, and (c, d) the fundamental harmonic interaction, corresponding to the cutaway plots of Fig. 8 and Fig. 9, respectively, in momentum phase space at the axial sections of (a, c) $z = 0.30 \sim 0.32$ m, and (b, d) $z = 0.38 \sim 0.40$ m.

**B. RF Properties**

Figure 11 represents frequency spectra obtained by the fast Fourier transformation (FFT) of the electric fields $E_y$ in both the input and the output stages from MAGIC2D simulation. The electric field in the input stage driven at 11.8 GHz is normalized by the amplified electric field in the output stage. The magnitude of FFT of the third-harmonic electric field at 35.4 GHz shows that it is amplified by a factor of approximately 18, which corresponds to about 24 dB in the power scale. Here, it should also be noted that only odd harmonics appear in both the input and the output stages due to the parity of electron cyclotron resonance [28]. The fundamental harmonic at the X-band frequency is the cutoff in the output stage and the higher harmonics are negligible such that harmonic purity is achieved by more than 60 dBc even at the fifth and the seventh harmonics.

The characteristics of the output amplified power are shown in Fig. 12. The results are predicted by the self-consistent large-signal theory and the particle-in-cell code MAGIC2D simulation. The large-signal theory calculates an instantaneous full width at half-maximum (FWHM) bandwidth (i.e., constant drive 3 dB bandwidth) of 3.8% and a peak power of 3.64 kW corresponding to a small-signal gain of 24 dB when a 30-kV, 1-A axis-encircling electron beam with no velocity spread is assumed. Under the same operating condition as listed in Table 1, the MAGIC2D simulation results appear to be in good agreement with the large-signal theory. The stably amplified output power is obtained in the time domain and shows a slightly reduced bandwidth and peak power.

Fig. 11. Simulated frequency spectra of the input and the output stages, where a drive signal of 11.8 GHz in the input stage produces an amplified third-harmonic frequency of 35.4 GHz in the output stage.

Fig. 12. Amplified output power and the instantaneous bandwidth using the self-consistent large-signal theory and the particle-in-cell code MAGIC2D for a 30-kV, 1-A axis-encircling electron beam with a beam velocity ratio $\alpha$ of 1.6.

The growth of the output power at the end of the output stage in the time domain is illustrated in Fig. 13 using the
particle-in-cell code MAGIC2D. With respect to input drive powers from 10 to 30 W at 11.8 GHz, amplified powers at 35.4 GHz are shown. Here, the emission of the electron beam starts at 6 ns for a fill-up time of the input drive power in the input stage. At about 17 ns, the beam head passes through the end of the output stage. As shown in Fig. 13, stable and stationary output powers driven by different input levels are expected at the third-harmonic frequency of 35 GHz. In addition, there appears to be saturation of the amplified output power of about 3 kW when the drive power is about 20 W.

The intrinsic nonlinear behavior of the harmonic frequency multiplier is indicated in Fig. 14. It represents the power scaling law of the beam-wave interaction as given by $P_{\text{out}} = K \cdot P_{\text{in}}^s$, where $P_{\text{out}}$ is the amplified output power, $K$ is the tube-dependent constant, and $P_{\text{in}}$ is the harmonic number $s$th power of the input drive power $P_{\text{in}}$ [18]. Here, the fundamental-harmonic interaction in the input stage shows that the output power from the input stage is proportional to the input drive power corresponding to a linear gain of about 6 dB; however, the third-harmonic interaction in the output stage leads to a cubic power relation. In other words, the constant gain in the input stage means the interaction constitutes linear amplification by the fundamental-harmonic operation; however, the gain in the output stage increases following the cubic power-scaling law ($K \approx 5.7$) such that the interaction constitutes nonlinear amplification by the third-harmonic operation. This indicates that nonlinear behavior appears even in the small-signal regime. The drive curves in both stages calculated by the large-signal theory also show reasonable agreement with the MAGIC2D code.

IV. MEASUREMENT OF FREQUENCY MULTIPLICATION

In the experiment, the third-harmonic frequency-multiplying gyro-TWT amplifier system consists of four parts. The first is the input drive part using a helix-TWT amplifier which amplifies an X-band small signal from a synthesized signal generator (Anritsu 68167C). Secondly, to generate an axis-encircling electron beam for the gyro-TWT amplifier, a 30-kV pulsed modulator is employed and synchronized within the pulse width of the input drive from the helix-TWT amplifier. Thirdly, there are three DC power supplies for 10-A gun magnets, one for a 70-A main magnet, and thirteen for 10-A sub magnets. These magnets are controlled by a computer-based program LabVIEW. Finally, the RF measurement system is prepared for the measurements of frequency multiplication and power amplification. The frequency multiplied output frequency is accurately measured by a spectrum analyzer HP8565E with a time-gated function and a sweep time of 60 s. For the power measurement in both X-band and Ka-band frequencies, a peak power meter HP8991A is utilized with peak power sensors.

To investigate the taper sensitivity of the output power and bandwidth, two different designs of the interaction circuit are considered, such as Taper-I and Taper-II as shown in Table 1. These designs have different cutoff frequencies in the output stage. Taper-I is chosen to have a broad bandwidth. The angles of the output stage taper in both cases are 0.00224° and 0.00119°, respectively. Owing to such a weak taper angle, the fabrication error along the output stage may cause serious adjustment of the performance of the amplifier. Figure 15 depicts the comparison of the effects of Taper-I and Taper-II on the output power and the bandwidth versus output frequency calculated by the large-signal theory. The figure shows quite a large difference in both cases. The output power changes by about 10 dBm and the 3dB bandwidth differs by one half. The theoretical analysis of the previous Section III is based on the case of Taper-II for efficient power amplification. However, the design of Taper-I is chosen in the beginning stage of the experiment for a feasibility study on the bandwidth. The next
stage of the experiment will adopt the Taper-II scheme or more improved taper design.

The measured output power versus the measured output frequency using the design of Taper-I is depicted in Fig. 16. Through comparison of theoretically predicted and experimentally measured output powers when the beam current is 160 mA, the output power at Ka-band frequency shows sensitive dependence on the axial velocity spread of the electron beam. When there is no spread, the output power may reach more than 30 dBm as predicted by the large-signal theory and the MAGIC2D code. However, significant reduction of the output power and the bandwidth are observed and it may be explained by the effect of sensitivity on the axial velocity spread. Since the tapered interaction circuit is utilized in both stages, the beam velocity spread can easily cause the beam-wave interaction to be out of resonance [29]. This is due to the effectively reduced interaction length by tapering the interaction circuit. In other words, the distributed interaction with such a short interaction length is susceptible to the beam velocity spread; however, the tapered scheme is chosen to improve the bandwidth and the stability from spurious oscillations in low-voltage operation as discussed before. Furthermore, the third-harmonic interaction in the output stage is intrinsically vulnerable to the velocity spread on account of weak beam-wave coupling [19], [28], showing about 15 dBm output power reduction. Considering the effect of the axial velocity spread, the measurements of output power and frequency multiplication are carried out when the spread is about 10%. Such a large spread may derive from the low quality of the emission surface of the cathode due to the degradation of the beam current which originally produces 1 A. However, the frequency multiplication is verified by the experimental observation of the output frequencies from 31.8 GHz to 36 GHz, corresponding to the input drive frequencies from 10.6 GHz to 12.0 GHz.

The measured output frequency and the input drive power including the output power of the gyro-TWT are illustrated in Fig. 17. For example, an output frequency of 35.4 GHz is observed by the Ka-band frequency meter with the crystal detector and is also precisely measured by the spectrum analyzer HP8565E, which is depicted in Fig. 17(a). The frequency-multiplied signal corresponds to three times an input drive frequency of 11.8 GHz. Neither the drive frequency, nor the second harmonic frequency is observed as predicted due to the complete cutoff of the frequencies and the parity of the interaction. Figure 17(b) (upper) represents the input drive power from the helix-TWT with a 24-µs pulse width and a 20-Hz repetition rate at 11.8 GHz. The 35-GHz output power (lower) from the third-harmonic frequency-multiplying gyro-TWT is also measured by the peak power meter with a synchronized pulse width of 12 µs provided by a 30-kV pulsed modulator. The frequency multiplication from X-band to Ka-band frequencies is verified, which corresponds to three times the input drive frequencies, as expected.

V. CONCLUSION

Theoretical predictions and measurements including the experimental design and setup of the third-harmonic frequency-multiplying gyro-TWT amplifier were presented. The self-consistent large-signal theory and the particle-in-cell code simulation showed good agreement and predicted the frequency multiplication. By using the particle-in-cell code MAGIC2D, the evolution of the electron bunch by the third-harmonic interaction was investigated and revealed the combination of a fundamental-harmonic electron bunch and two relatively weak bunches generated by the third-harmonic interaction. An instantaneous bandwidth of 3.8% and a peak power of 3.64 kW corresponding to a small-signal gain of 24 dB were also predicted when a 30-kV, 1-A axis-encircling electron beam
with no axial velocity spread was assumed. Experimentally, the frequency multiplication from X-band to Ka-band frequency by the third-harmonic interaction of the electron cyclotron resonance was verified in low-voltage and low-current operation of 30 kV and 160 mA, respectively. Therefore, power amplification exceeding 65 dBm can also be reliably expected when the beam emission is improved up to 1 A and the Taper-II design is employed under the precise control of the axial velocity spread. Such an experimental investigation on both frequency multiplication and power amplification is underway.

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REFERENCES

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