Operation of a Highly Overmoded, Harmonic-Multiplying, Wideband Gyrotron Amplifier

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Experiments on a unique, high-power, millimeter wave amplifier (a phase-coherent, harmonic-multiplying, inverted gyrotwystron) are reported. Superior stability resulted from two factors: (1) interaction between a relatively low order waveguide mode (TE_{22}) and the beam wave at the fundamental cyclotron frequency in the input section, and (2) an internal mode filter in the highly overmoded (TE_{42}), second harmonic output cavity. Bandwidth was 1.3% with peak gain of 33 dB around 31.8 GHz. The gain-bandwidth performance is a significant advance for gyrotron amplifiers operating in such high order modes. [S0031-9007(97)03586-2]

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Recently there has been considerable interest in the development of compact, high-power millimeter wave amplifiers, for advanced radar and communication applications. Gyrotron oscillators operating in very high order modes have been capable of generating unprecedented levels of average power in the millimeter and submillimeter wavelength range [1]; however, they have the disadvantage of a high magnetic field requirement. These two factors have largely dictated the trends of gyrotron amplifier research in recent years. Significant effort has been devoted toward the realization of the high-power capability of the gyrotron by utilizing high order modes. On the other hand, harmonic operation has also been the subject of active research in order to alleviate the magnetic field requirement. However, the extra degrees of freedom provided by both the high order modes and a multitude of cyclotron harmonics tend to generate spurious interactions. Mode competition thus constitutes the principal physics and technology issue common to high-power and high harmonic gyrotron research and development. Studies of multimode interaction processes under various conditions have shed much light on the physics of mode competition [2–9] and major advances in high-power and high harmonic gyrotrons have been reported [10–18]. Good performance has been achieved for gyrotron amplifiers operating in relatively low order modes TE_{01} [3,4,18,19] or TE_{21} [13]. However, interest in very high average power, millimeter-wave amplifiers has led to studies of TE_{02} mode, two-cavity, gyroklystron amplifiers operating at 35 GHz; this frequency corresponded to the second harmonic of the electron cyclotron frequency in one study [16] and to the first harmonic in another study [17]. In the case of the TE_{02}, second harmonic gyroklystron, performance was limited by instabilities, and only modest gain and bandwidth were achieved; i.e., gain of 17 dB, bandwidth of 0.1%, and product of voltage gain and bandwidth $\cong$ 200 MHz. For the TE_{02} gyroklystron operating at the fundamental of the electron cyclotron frequency, bandwidth was better (0.6%) but gain was limited to 20 dB in the two-cavity circuit, and practical difficulties were encountered in developing such amplifier with more than two cavities; the product of voltage gain and bandwidth was 2000 MHz.

One path to enhance stability is suggested by studies of the harmonic multiplying, gyroklystron amplifier [11]. Here the input cavity was operated at one half the output frequency in the TE_{01} mode while output was at the second harmonic cyclotron frequency in the TE_{02} mode. The harmonic-multiplying gyroklystron amplifier has been experimentally demonstrated at frequencies near 19.76 GHz in the high-energy pulse-power regime (437 kV, 232 A), with performances pushing the state of the art for amplifiers in terms of the microwave pulse energy divided by output wavelength squared [11,20]; gain was 30 dB in a two-cavity configuration although bandwidth was only $\sim$0.1%. The harmonic-multiplying gyroklystron has also been extensively treated theoretically [21,22].

This Letter reports on the experimental study of a novel type of gyrotron amplifier which is hybrid of a *gyrotron traveling wave tube* (gyro-TWT) and a phase-locked gyroklystron oscillator with subharmonic injection [23] in a configuration of inverted gyrotwystron. Compared to the gyroklystron, it may have significantly wider bandwidth while maintaining large gain due to replacing the input cavity with a traveling wave interaction structure. The product of gain and bandwidth is an index of vital importance especially for radar applications.

The configuration of the inverted gyrotwystron is shown schematically in Fig. 1. The device uses a magnetron injection gun (MIG) to produce its electron beam. The drive signal is applied via a Ku-band (14–20 GHz) input coupler. By amplification of the drive wave through fundamental harmonic ($s = 1$) cyclotron maser interaction in the gyro-TWT section, the signal at harmonics of the drive frequency is nonlinearly generated in the electron beam. The amplified wave is absorbed in a matched load at the end of the gyro-TWT section, but all harmonic components in the beam current continue through into the drift section and further develop by ballistic bunching. Tuning is such that the second harmonic component

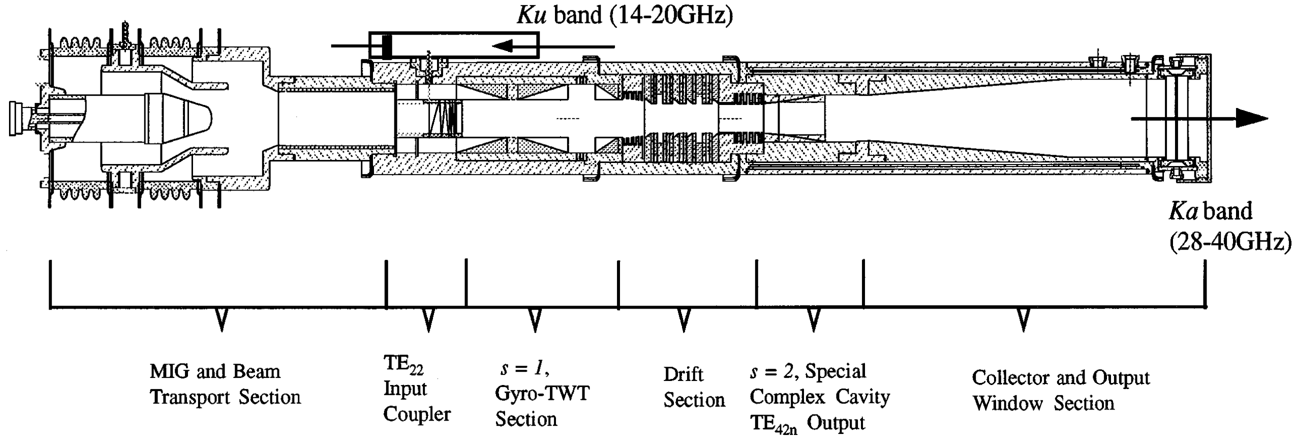

FIG. 1. Two stage, phase-coherent, harmonic-multiplying, inverted gryotwystron (phigtron). Overall length 1.2 m. Arrows indicate input and output microwave signals.

reaches an optimum value when the beam reaches the output cavity; there a cavity mode is excited which is resonant at twice the frequency of the driving signal. This cavity mode rapidly grows through the second harmonic ($s = 2$) cyclotron maser interaction. The Ka-band (28–40 GHz) output power is axially extracted and travels to the vacuum window while the spent beam dumps in the collector region. The growth process of harmonic components in the beam current is a nonlinear aspect of cyclotron maser bunching, and provides the basis for harmonic multiplication. This nonlinear behavior has been predicted by both particle-in-cell simulation and analysis (to be published elsewhere [24,25]). Figure 2 shows the growth of harmonic components along the tube axis which is predicted by a self-consistent large signal code with operating parameters similar to those used in the experiment. The fast growth of the third harmonic component ($s = 3$) gives promise of higher harmonic multiplication in future studies.

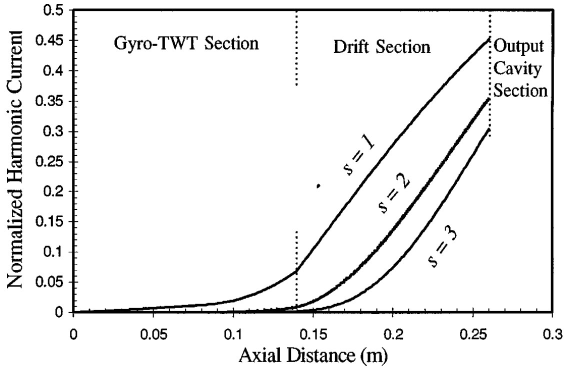

FIG. 2. Calculated spatial evolution of harmonic components in the beam current. The phigtron utilizes a TE_{22} gyro-TWT as prebunch section with assumed values of the parameter as follows: beam voltage 58 kV, current 12 A, velocity ratio ($v_{\perp}/v_{\|}$) 1.5, input power 10 W, and TE_{22} mode in the gyro-TWT section.

By simple nonlinear arguments, we obtained a relation between the drive signal phase, ϕ_d, and the output signal phase, ϕ_{out}, given by

$$\Delta\phi = \phi_{out} - 2\phi_d = \text{const.} \tag{1}$$

Thus, the output radiation of the inverted gyrotwystron can be phase controlled by the drive source. When operating conditions are tuned below start oscillation, the device operates as a frequency multiplying amplifier, otherwise, it is a phase-locked oscillator.

The input coupler/mode launcher shown in Fig. 1 incorporates a rectangular-coaxial structure and a novel complex helix antenna made by winding silver wire (diameter = 0.3 mm) on a ceramic substrate with a gradually changing pitch angle from 45° → 0°. Theoretically, this structure can excite the coaxial waveguide $\mathrm{TE}_{01}^{\odot}$ and $\mathrm{TE}_{21}^{\odot}$ modes [26], but when the drive frequency is below 16.38 GHz, only the $\mathrm{TE}_{21}^{\odot}$ can be excited. The input coupler feeds the gyro-TWT section which consists of a slotted wall section supporting mixed modes followed by a smooth waveguide of diameter 40.88 mm where the TE_{22} mode propagates for frequencies above its cutoff of 15.65 GHz. The overall length of the gyro-TWT interaction region is 14 cm.

The radiation-free drift section is constructed by stacking a series of lossy metal and ceramic washers as well as two honeycomblike absorbers (sprayed with FeNiCrCoAl alloy) inside the housing with total length of 14 cm and minimum diameter of 1.75 cm. The output cavity, 9 cm in length, is derived from a previously studied Ka band, second harmonic, free running, gyrotron oscillator [10,27] with changes made only to the tapered cutoff waveguide on the input side and the output coupling aperture. In this new version, the cutoff section is a gradual, lossy taper in place of the tapered smooth waveguide, and the diameter of the coupling hole is enlarged from 2.75 to 2.83 cm. These changes reduce the Q factor of the cavity from 1500 to ~600 for various axial modes, and broadband operation is expected. Since the output cavity contains an internal mode filter with eight radial conducting vanes arranged periodically around the azimuth which are consistent with $(\mathrm{TE}_{42})_l$ modes (axial eigennumber $l = 1, 2, 3, 4, 5\ldots$). The resonant frequency for $(\mathrm{TE}_{42})_l$ modes is in the range from 31.5 to 32.4 GHz with $l = 1-6$. These axial modes of the output cavity together with the gyro-TWT broadband prebunching allow the amplifier to operate over a wide frequency range. We note that the following theoretical condition [22] is satisfied:

$$s_1 m_2 = s_2 m_1 , \tag{2}$$

where s is the harmonic number, m is the azimuthal index of the interacting TE mode, and the subscripts 1 and 2 refer to the input gyro-TWT section and the output cavity, respectively.

The inverted gyrotwystron is powered by a modulator which provides a flat pulse of 30–60 kV with a pulse length of 7.7 μs and a variable repetition rate of 20–300 Hz. The MIG produces a beam current up to 12 A. Five independent dc current supplies power the water-cooled solenoid magnets that allow for considerable variation in the axial magnetic field profile. The field in the interaction region is increased from 0.56 to 0.68 T over a 35 cm distance. Computer simulation indicates that the velocity ratio typically achieved in the experiment is ≤ 1.5. The corresponding axial velocity spread is in the $\sim 8\%-10\%$ range and depends on the beam current and the voltage applied to the intermediate anode. A Ku-band, pulsed, helix TWT provides the input power. Output power is measured by a calibrated calorimeter. Details of the diagnostic setup are shown in Fig. 3. A harmonic mixer/phase detector is used to compare the input and output frequencies and identify the relative phase relation. The output signal is also characterized by a spectrum analyzer.

Although the inverted gyrotwystron was initially designed as a phase-locked oscillator, it can be operated as an amplifier by modifying the magnetic field profile so that the output cavity is detuned below threshold of oscillation in the absence of an input signal. Measured saturated output power is plotted as a function of output frequency at the applied voltage of 58 kV and beam current of 9.2 A in Fig. 4(a). Measurement gives ~33 dB gain and 1.3% continuous bandwidth (410 MHz) around 31.8 GHz as well as an amplification range of 820 MHz from 31.33 to 32.15 GHz but with two narrow gaps each about 50 MHz. Measured power is also plotted as a function of beam current at the same operating voltage of 58 kV for the sharp, high-power spectral peak at 31.525 GHz giving a value of ~160 kW with

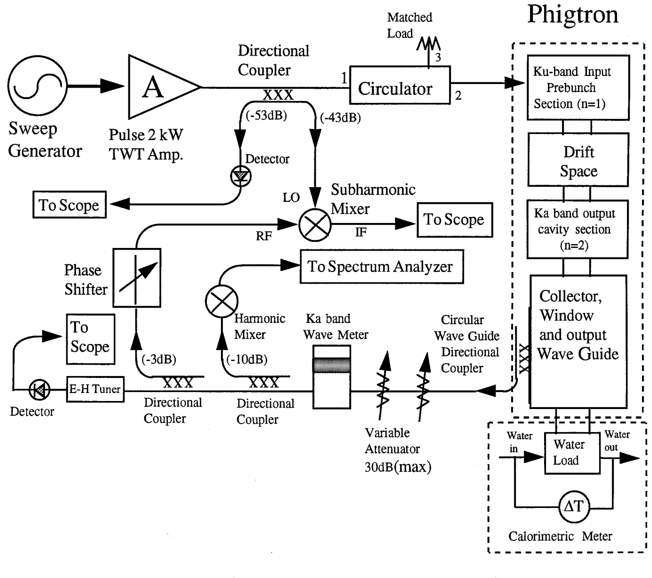

FIG. 3. Schematic of the experimental setup for the phigtron diagnostic.

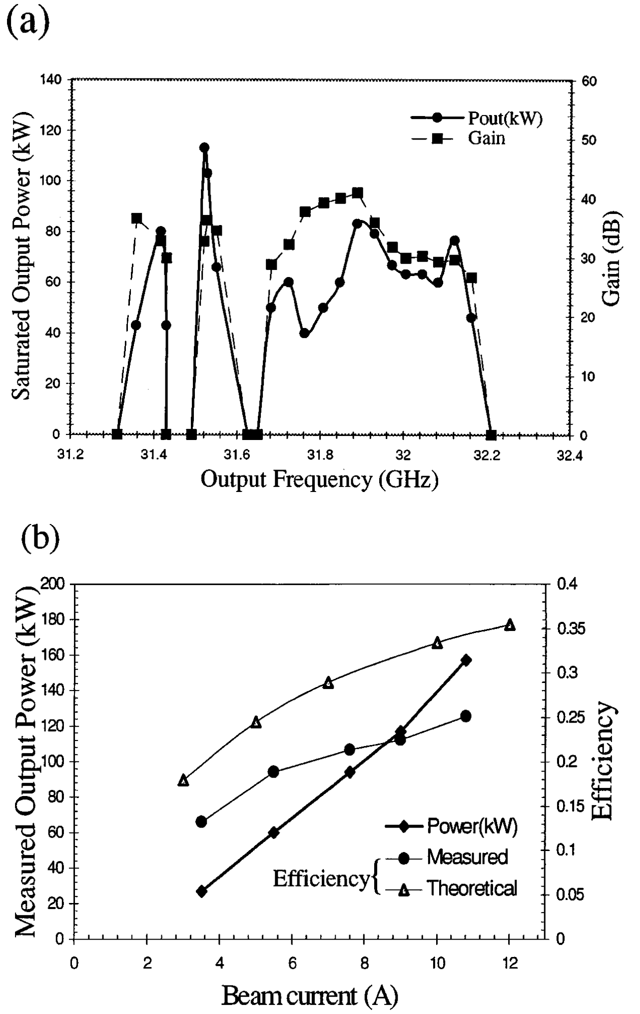

FIG. 4. Experimental and theoretical results of phigtron amplifier with TE_{42} mode output. (a) Dependence of measured saturation power and small signal gain on operation frequency for a fixed beam voltage of 58 kV and current of 9.2 A. (b) Peak power and efficiency measured as well as calculated as a function of beam current for a fixed beam voltage at 58 kV.

corresponding efficiency of 25% and gain of 35 dB as shown in Fig. 4(b).

The input frequency of the amplifier is at exactly half of the output frequency, and the phase of the output signal was observed to be locked to twice the phase of input signal. The occurrence of phase locking was detected by varying the phase shifter in one of the arms feeding the subharmonic mixer as shown in Fig. 3 and observing indication of a fixed phase relationship between the amplified input and output signals in the mixer output. Frequency locking was verified by using the spectrum analyzer and observing that the amplifier output frequency is pulled to follow variation in the injection signal frequency.

No spurious oscillation was observed, a fact we attribute to the merits of both using a relatively low order mode combined with the $s = 1$ interaction in the input section and the use of a vaned mode filter in the output section. Based on the analytical theory which is given in Ref. [22], simulations using a smooth waveguide interaction circuit and assuming an ideal electron beam without velocity spread were performed. The main computational results are also shown in Fig. 4(b) for comparison with the measured data. The agreement between measured and theoretical amplifier efficiency is reasonable in light of the approximation and assumptions described above.

In summary, we have demonstrated experimentally a highly overmoded, millimeter wave source in an inverted gyrotwystron configuration with frequency/harmonic multiplication and internal mode filters for stable operation. Amplifier peak power of 160 kW is achieved in the TE_{42} mode in a narrow peak around 31.525 GHz. Stable amplification is observed with a bandwidth of 1.3% and gain of 33 dB around 31.8 GHz, corresponding to the product of voltage gain and bandwidth $\cong 18\,000$ MHz. The measured gain-bandwidth performance is almost an order of magnitude beyond the previous state of the art for a highly overmoded gyrotron amplifier operating at either the fundamental cyclotron frequency or the second harmonic of the cyclotron frequency. Future studies will look into the average power that can be achieved around 35 and 94 GHz and into third and fourth harmonic operations.

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