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EXPERIMENTAL MEASUREMENTS OF COMPETITION BETWEEN FUNDAMENTAL AND SECOND HARMONIC EMISSION IN A QUASI-OPTICAL GYROTRON

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Experimental measurements of competition between fundamental and second harmonic emission in a quasi-optical gyrotron

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Abstract

A quasi-optical gyrotron (QOG) designed for operation at the fundamental ($\Omega_{ce} \simeq 100$ GHz) exhibits simultaneous emission at Ω_{ce} and $2\Omega_{ce}$ ($2^{\rm nd}$ harmonic). For a beam current of 4 A, 20% of the total RF power is emitted at the $2^{\rm nd}$ harmonic. The experimental measurements show that the excitation of the $2^{\rm nd}$ harmonic is only possible when the fundamental is present. The frequency of the $2^{\rm nd}$ harmonic is locked by the frequency of the fundamental. Experimental evidence shows that when the $2^{\rm nd}$ harmonic is not excited, total efficiency is enhanced.

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The generation of second and higher-order harmonics in gyrotrons has been reported by many groups [1,2]. The mechanism is either the electromagnetic cyclotron maser instability [1] or the electrostatic Bernstein modes [2,3,4]. In this Letter, results on competition between the fundamental and the 2nd harmonic in a quasi-optical gyrotron (QOG) are presented.

The experimental set-up is described in detail in Reference 1. A temperature -limited MIG triode-electron-gun, operating at voltages up to 70 kV and currents up to 11 A, generates an annular electron beam with a mean radius of $r_b = 2.23$ mm. The experimentally optimized [5] pitch $\alpha \equiv \langle v_\perp / v_\| \rangle$ is 1.12 with a dispersion $\Delta\alpha/\alpha = 6\%$. Magnetic fields of up to 3.96 T in the interaction region and 0.25 T at the gun is generated by a pair of superconducting (SC) Helmholtz coils and a pair of SC gun coils. A large diameter vacuum vessel (diameter $\simeq$ 40 cm) is mounted in the inner bore of the Helmholtz coils. It accomodates the beam tunnels, the Fabry-Perot resonator and the collector. For this experiment, a "large resonator" made of gold-plated copper (DC gold conductivity $\sigma = 4.2 \times 10^7 \Omega^{-1} m^{-1}$) with mirrors of 50-cm radius of curvature, 13.6-cm diameter and an adjustable separation, d, of $32.9 - 34.9$ cm has been used. The output coupling is purely diffractive; the RF being coupled out through annular slots in the output mirror. The microwave power is coupled out equally around each mirror and flows through two overmoded waveguides (diameter = 8.69 cm) towards two, 125-μm thick, kapton vacuum windows. For operation at the fundamental ($\omega \simeq \Omega_{ce} \simeq 100$ GHz), because of the high diffraction losses for the higher order transverse modes ($TEM_{m,n,q}, m \geq 1, n \geq 1$, m, n, q are respectively the azimuthal, radial and longitudinal indeces), only the Gaussian modes ($TEM_{0,0,q}$) has a quality factor high enough to allow oscillation to start. The computed total quality factor (including diffractive and ohmic losses) is 33200 ($TEM_{0,0,227}$), the ohmic losses of the mirrors are of the order of 5% of the total diffracted power. The radiation waist is $w_{01} \simeq 5\lambda_1$ where λ_1 is the wavelength of the radiation at the fundamental. For 2nd harmonic operation, two transverse mode ($TEM_{0,0,q'}$ and $TEM_{1,0,q''}, q'$ and $q'' = 454$ to 456) have quality factors high enough to allow oscillation to start. For the $TEM_{0,0,454}$ (gaussian mode at the 2nd harmonic), the ohmic losses are almost 10 times the diffractive losses. The total quality factor ($Q = 880000$) is therefore almost due entirely to ohmic losses. The transmission T corresponding to the diffraction losses is 0.032%. The output coupling efficiency is of the order of 90% and the radiation waist radius is $w_{02} \simeq 7.2\lambda_2$, where λ_2 is the wavelength of the radiation at the 2nd harmonic. For the $TEM_{1,0,q''}$ mode the ohmic losses are almost equal to the diffraction losses. The total quality factor is 460000 and the transmission, T, is 0.33%. For the $TEM_{1,0,q''}$ the electric field profile inside the resonator is no longer gaussian but is null at the resonator center along the static magnetic field axis. The frequency spacing between longitudinal modes (for fixed transverse indeces) is 444 MHz. A summary of the resonator mode characteristics is given in Table 1.

The diagnostic for the simultaneous measurement of the 100 GHz and 200 GHz emission is shown in Fig. 1. The RF power is split into two parts by a mylar foil. The transmitted signal, after -50 dB attenuation through a layer of Octanol ($C_8H_{18}O$), is down converted to an IF at $8 - 12$ GHz via a mixer driven by a tunable Gunn diode. For the studies of the fundamental emission (100 GHz), a fundamental mixer ($n = 1^+$) is used while for the second harmonic measurements, we use a 2^{nd} harmonic mixer ($n = 2^+$). The IF signal is fed into a 16-channel narrow-band (300 MHz) multiplexer which allows the time-resolved analysis of the RF emission. In order to make more precise frequency measurements, a spectrum analyser with much narrower adjustable bandwidth ($0.1 - 3.0$ MHz) is connected to the IF signal. The reflected power is collected by a D-band microwave horn and is used for the measurement of the relative power content in the first and 2^{nd} harmonic. A 1.32-cm thick Macor plate which has a frequency dependent attenuation (α_i(100 GHz)= 0.75 Np/cm and α_i(200 GHz)= 2.0 Np/cm) can be placed in front of the detection horn as a verification of this power diagnostic. To avoid ambiguity in the frequency determination, both a high-pass filter (Attenuation: -60 dB at 100 GHz), and a low-pass filter (Cut-off at 165 GHz [6]) are used. In particular with the low-pass filter we have verified that the 2^{nd} harmonic signal is a true signal and is not generated by non-linear effects in the frequency measurement set-up.

The measured threshold currents of the fundamental and the 2^{nd} harmonic are equal and are as low as 500 mA. A time-resolved trace of the signal emitted at the fundamental and 2^{nd} harmonics is shown in Fig. 2. The upper trace shows the time evolution of the total power (100 GHz + 200 GHz) whereas the other traces correspond to the outputs of 7 of the 16 channels of the multiplexer and give the time evolution of the excited mode at the second harmonic. The beam current for this case is 850 mA. Although in some cases the 2^{nd} harmonic is excited with some delay relative to the fundamental, for currents higher than the threshold, we always observed excitation of both harmonics with pulses of 10-ms duration. Figure 3 shows the frequency variation of both harmonics versus the mirror separation at a beam current $I_b = 4$ A. The narrow band-pass filter of the spectrum analyser gives an accuracy on the frequency measurement of the order of 0.03 %. This clearly indicates that the frequency at the 2^{nd} harmonic is exactly twice that of the fundamental.

The excitation of the 2^{nd} harmonic is strongly dependent on the beam characteristics. Figure 4 shows the power variation of the 2^{nd} harmonic and the total power versus α. Notice that when the 2^{nd} harmonic is excited the total power is strongly decreased. The excitation of the 2^{nd} harmonic versus beam current is shown in Fig. 5. No quantitative comparison of the relative strengths of the total emission and the 2^{nd} harmonic emission should be inferred from this figure as the two signals are measured with two different diodes and for the 2^{nd} harmonic measurement we use a D-band detector and therefore the responsivity at 200 GHz is not known. Nevertheless, Fig.5 serves to illustrate several important qualitative features. Typically, two regions of excitation appear. The first region corresponds to low beam current ($I_b \simeq 1$ A) where the fundamental is almost suppressed and the 2^{nd} harmonic is at its maximum. The second region starts around $I_b \simeq 4$ A and is characterized by the coexistence of both the fundamental and the 2^{nd} harmonic. Similar observations were reported by Byerly et al [1]. The absolute total power and efficiency are respectively 90 kW and 12% for a beam current of 11 A. At the second harmonic, for $I_b \simeq 4$ A, 20% of the total power is emitted [5].

In order to compare these results with the theoretical prediction, Table 1 gives the characteristics of the unstable modes, the minimum starting current I_{st}, and the RF-power linear growth rate t_c^{-1}.The quantity t_c^{-1} is given by $t_c^{-1} = (\omega/Q)(I_b/I_{st} - 1)$ and is found from an energy balance equation in the linear regime: $dW_{EM}/dt + 2(\omega/Q)W_{EM} = \eta_{lin} I_b V_b$, where $\eta_{lin} = (\omega W_{EM})/(Q I_{st} V_b)$, ω is the mode frequency, W_{EM} is the resonator stored energy, V_b and I_b are the beam voltage and the beam current respectively. The minimum starting current ,I_{st}, is calculated assuming an $\alpha = 1.12$ and $V_b = 70$ kV, and the inverse of the RF-power linear growth rate is calculated for a beam current of 10 A. The measured starting current of the fundamental is lower than the theoretical value. The experimental frequency measurements show that the fundamental (ω_1) and 2^{nd} harmonic (ω_2), satisfy the following experimental rule: $\mid 2\omega_1 - \omega_2 \mid \leq 60(\pm 1)$ MHz. This indicates that the excited mode at the 2^{nd} harmonic cannot be gaussian, since this would require $\mid 2\omega_{0,0,q} - \omega_{0,0,2q} \mid = 170$ MHz. The only resonator mode which is compatible with the observed frequency is the $TEM_{1,0,q}$, which has a transmission large enough to couple out significant power. However, we observed 2^{nd} harmonic emission at a beam current equal to the starting current of the fundamental, which is lower than the theoretical predictions (see Table 1). A comparison of the RF-power linear growth rate (t_c^{-1}) for the different modes at $I_b = 10$ A, shows that the fundamental grows much faster than the 2^{nd} harmonic and could therefore inhibit the growth of the 2^{nd} harmonic modes. These simple considerations suggest that a mechanism different than the electron cyclotron maser instability might be responsible for the excitation of the 2^{nd} harmonic.

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References

[1] J.L. Byerly, B.G. Danly, K.E. Kreischer, R.J. Temkin, W.J. Mulligan, and P. Woskoboinikow, Int. J. Electron. **57**, 1033 (1984).

[2] N.A. Ebrahim, Z. Liang, and J.L. Hirshfield, Phys. Rev. Lett. **49**, 1556 (1982).

[3] A. Bondeson and T.M. Antonsen, Int. J. Electron. **61**, 855 (1986).

[4] T.M. Antonsen, W.M. Manheimer, and B. Levush, Int. J. Electron. **61**, 823 (1986).

[5] S. Alberti, M.Q. Tran, J.P. Hogge, T.M. Tran, A. Bondeson, P. Muggli, A. Perrenoud, B. Jödicke, and H.G. Mathews,to be published in Phys. Fluids B.

[6] B.W. Davis and R. Miller, Int. J. Infrared Millimeter Waves **6**, 3 (1985).

Table 1

Mode	q	f [GHz]	$Q \times 10^{-4}$	I_{st} [A]	t_c [ns]
$TEM_{0,0}$	227	101.14	3.32	2.1	14
$TEM_{0,0}$	454	202.11	88.0	0.944	72
$TEM_{1,0}$	454	202.29	46.0	3.81	222

Table 1 Frequency f, total quality factor Q, minimum starting current I_{st}, RF power linear growth rate $(t_c)^{-1}$

Figure captions

Fig.1 Frequency measurement setup for the 100 GHz signal (fundamental) and the 200 GHz signal (2^{nd} harmonic)

Fig.2 Time evolution of: the total power (upper trace) and 2^{nd} harmonic (7 channels of the 16 channel multiplexer) ($I_b = 850$ mA)

Fig.3 Frequency variation of both harmonics versus mirror separation ($I_b = 4$ A)

Fig.4 Total and 2^{nd} harmonic power (arbitrary units) versus α ($I_b = 1.5$A)

Fig.5 Excitation of the fundamental and the 2^{nd} harmonic versus beam current I_b

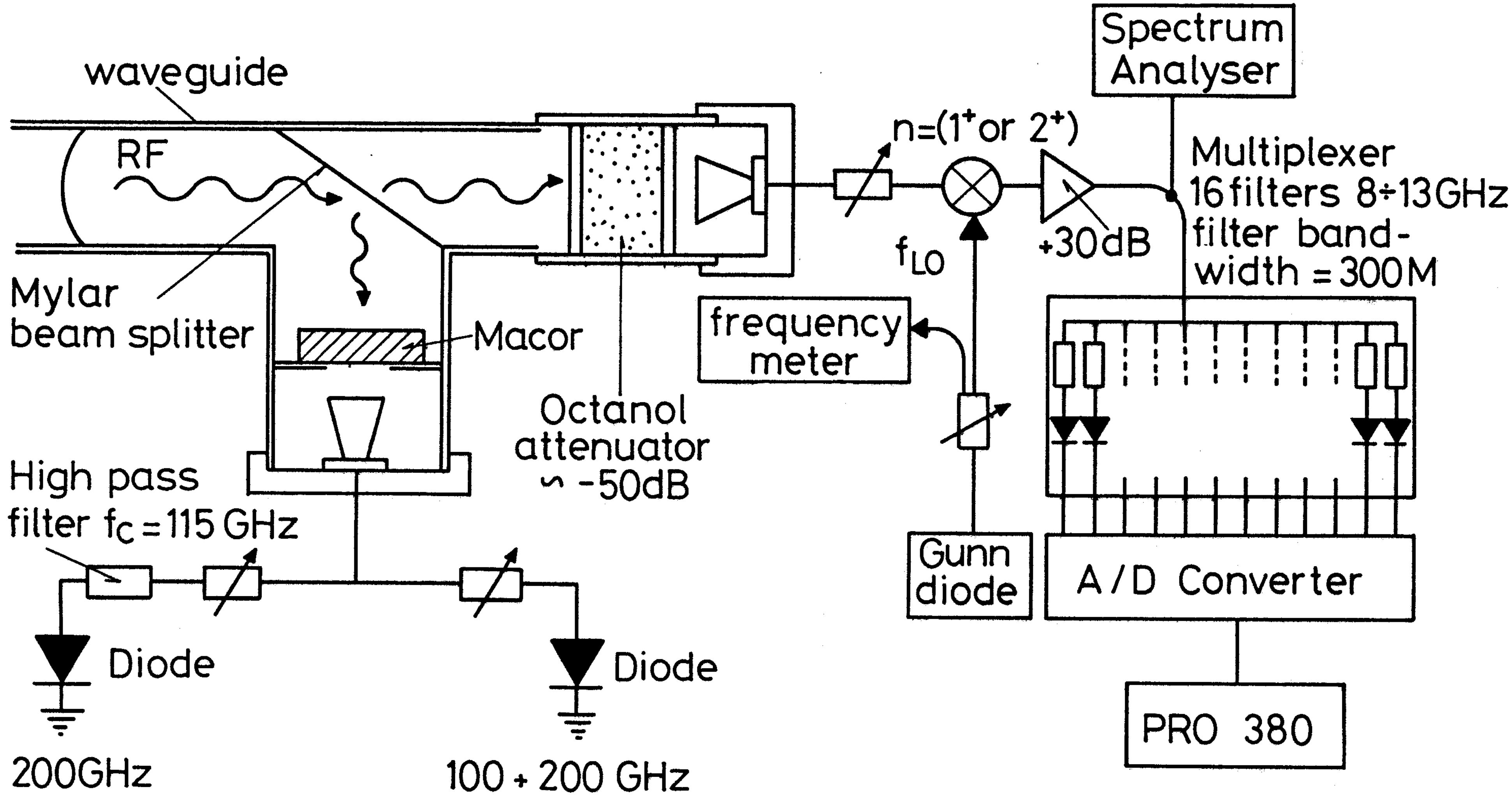

waveguide
RF
Mylar
beam splitter
Macor
Octanol
attenuator
∽ -50dB
High pass
filter fc = 115 GHz
Diode
200GHz
Diode
100 + 200 GHz
n=(1+ or 2+)
fLO
+30dB
frequency
meter
Gunn
diode
Spectrum
Analyser
Multiplexer
16 filters 8÷13GHz
filter band-
width = 300M
A / D Converter
PRO 380

Fig.1

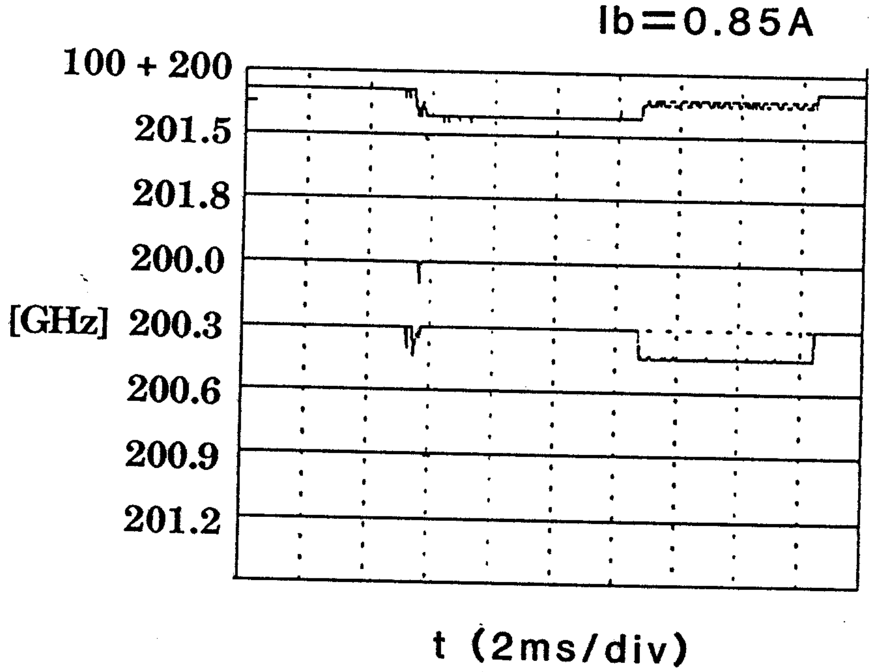
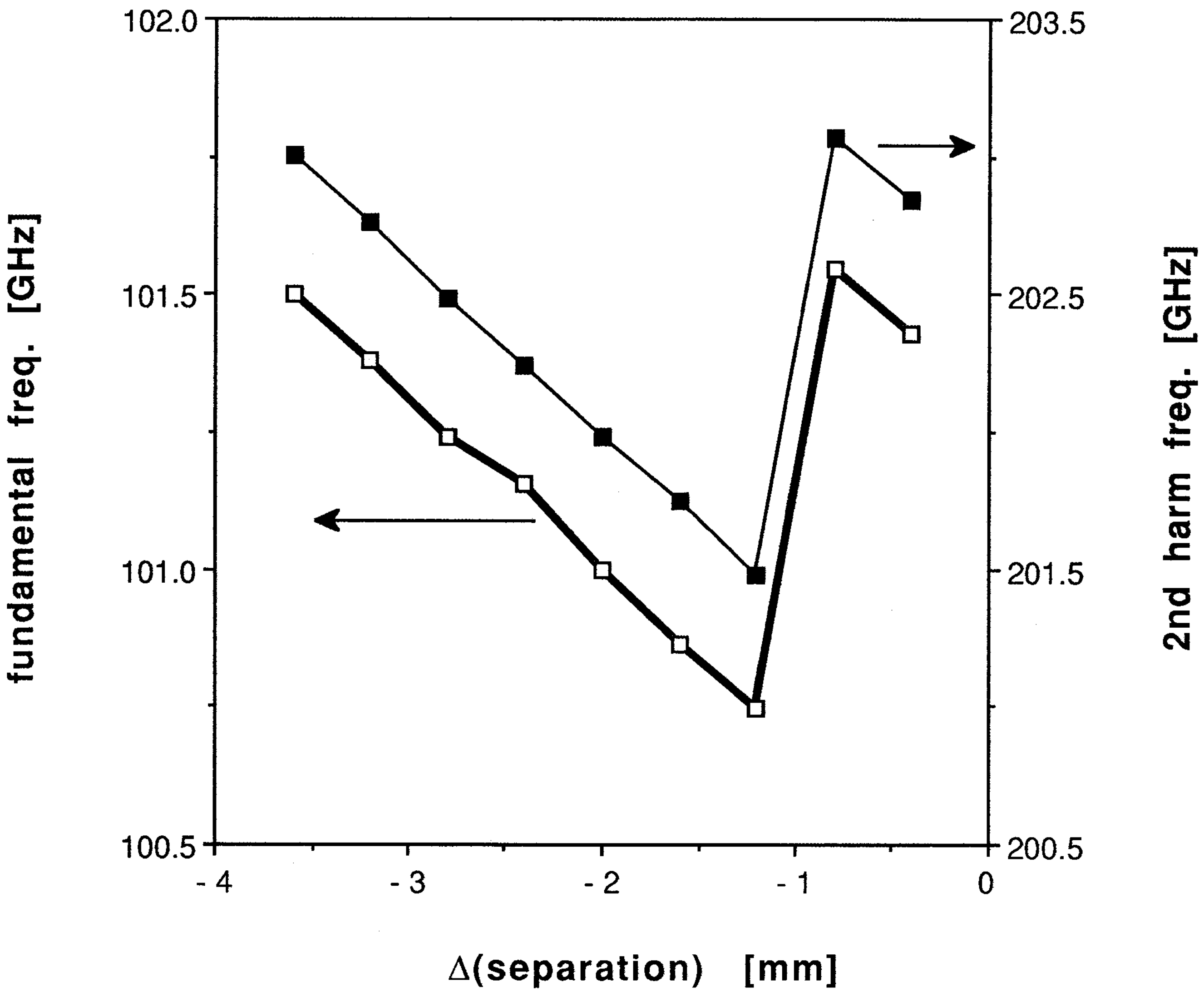

Ib=0.85A
100 + 200
201.5
201.8
200.0
[GHz]
200.3
200.6
200.9
201.2
t (2ms/div)

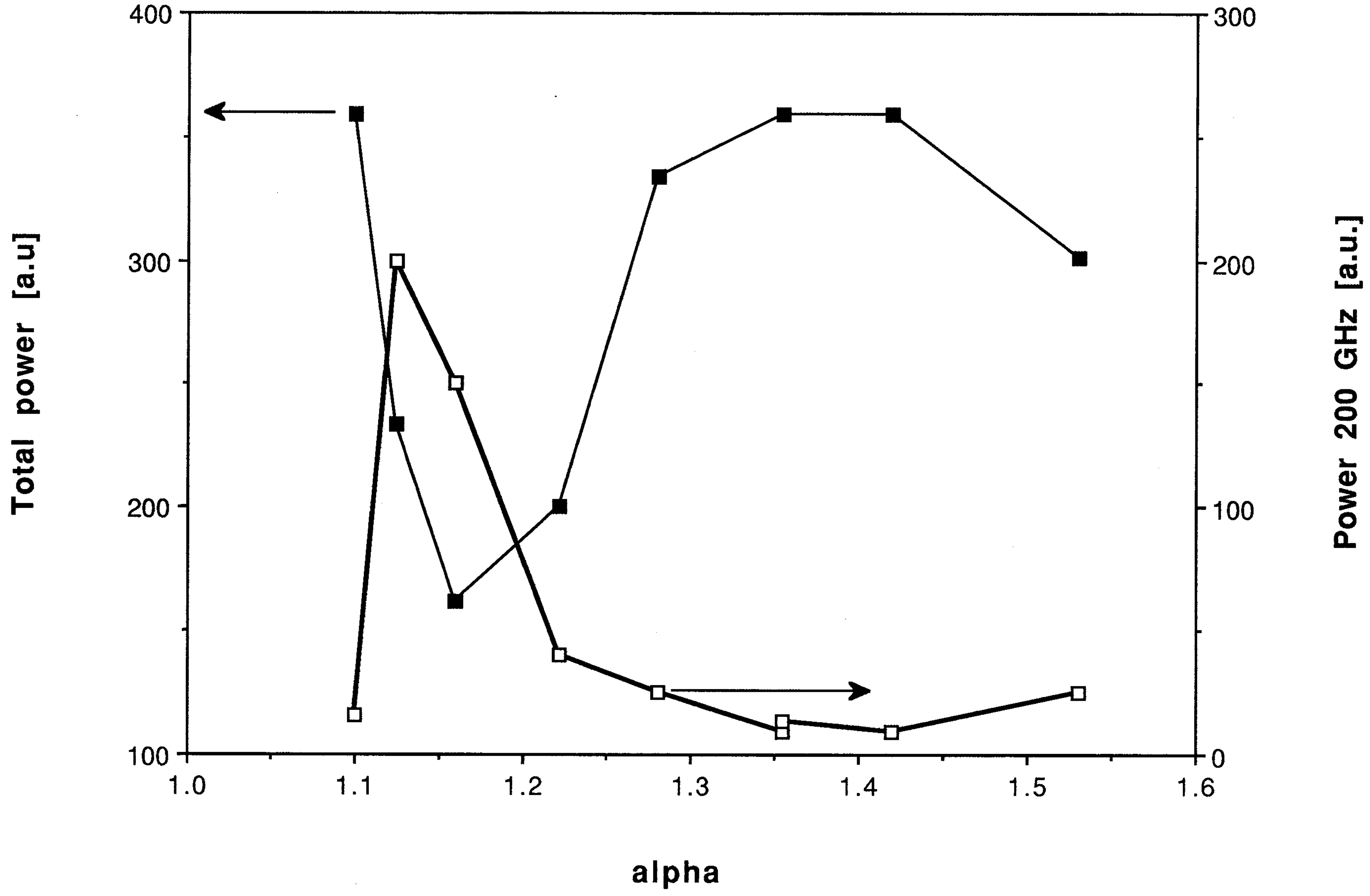
Fig.2

Fig.3



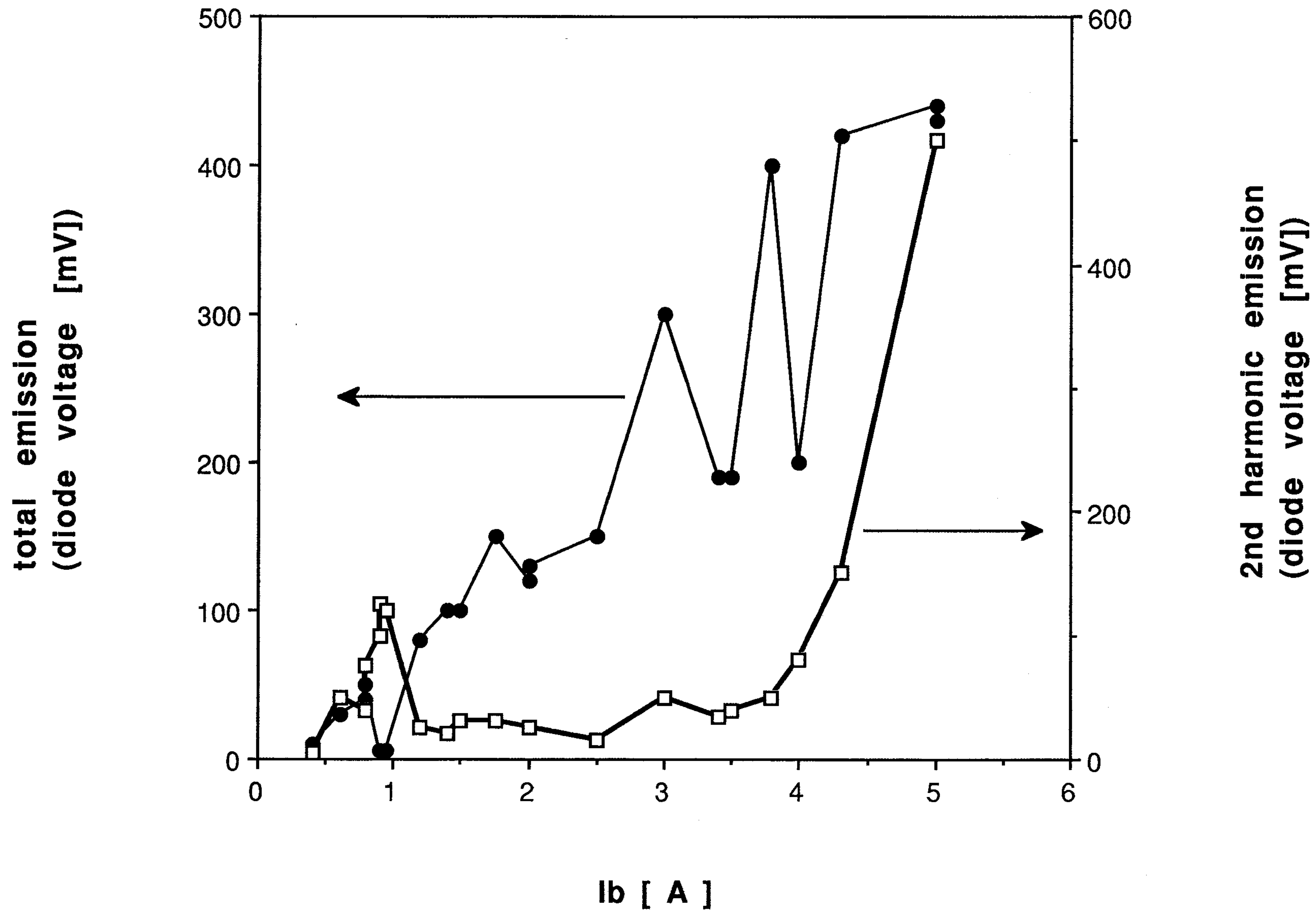
102.0
101.5
101.0
100.5
203.5
202.5
201.5
200.5
-4
-3
-2
-1
0
fundamental freq. [GHz]
2nd harm freq. [GHz]
Δ(separation) [mm]

Fig.4



Total power [a.u]
400
300
200
100
Power 200 GHz [a.u.]
300
200
100
0
1.0
1.1
1.2
1.3
1.4
1.5
1.6
alpha

Fig. 5


total emission
(diode voltage [mV])
0
100
200
300
400
500
2nd harmonic emission
(diode voltage [mV])
0
200
400
600
0
1
2
3
4
5
6
Ib [A]