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in a Free Electron Laser Amplifier**

K. Xu and G. Bekefi

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Department of Physics

and

Research Laboratory of Electronics

**Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA**

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EXPERIMENTAL STUDY OF MULTIPLE FREQUENCY EFFECTS IN A FREE ELECTRON LASER AMPLIFIER

K. Xu^{a)}, and G. Bekefi

**Department of Physics and Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139**

ABSTRACT

Measurements are presented of the gain and phase of a free electron laser (FEL) amplifier in the presence of a second, perturbing electromagnetic wave of different frequency. The studies are carried out in the microwave range of 7–11 GHz using a mildly relativistic electron beam of ~ 160 kV energy and a current of ~ 1 A. The presence of the perturbing wave causes serious deterioration of the FEL performance.

^{a)} permanent address: University of Electronic Science and Technology of China, Chengdu, China.

Multi-frequency studies can shed much light on the nonlinear dynamics and wave-particle interactions taking place in Free Electron Lasers (FEL). One well known example of such a multi-frequency effect is the appearance of side bands¹⁻³ in the FEL radiation spectrum. This phenomenon becomes particularly challenging when the radiation propagates in a highly dispersive waveguide (as is the case in our experiments) since now the different frequency waves are associated with a different ponderomotive wells, each of which travels at quite different velocity⁴. FEL amplifiers are usually not beset by side bands, unlike FEL oscillators in which side bands are readily excited¹⁻³ and are of much concern. Thus, we can examine multi-frequency phenomena in our amplifier in a controlled way by launching from external sources, two waves: one corresponding to the resonant FEL frequency f and a second, non-resonant perturbing wave of frequency f_0 . We then measure changes in the FEL gain and phase at frequency f caused by the presence of the wave at the neighboring frequency f_0 . All of our studies reported here were made in the collective (Raman) regime where space charge effects cannot be neglected.

Figure 1 shows a schematic of our experiment⁵. The accelerating potential is supplied by a Marx generator (Physics International Pulserad 615MR) which has a maximum capability of 500kV and 4kA. The electron beam is generated by a thermionically emitting, electrostatically focused, Pierce-type electron gun (≤ 250 kV, ≤ 250 A) from a SLAC klystron (model 343). An assembly of focusing coils transports the electron beam into the drift tube. To insure good electron orbits, an aperture acting as an emittance selector is inserted which limits the electron beam radius to $r_b = 0.245$ cm so that only the inner portion of the beam is used. With this precaution, the energy spread of the beam entering the magnetic wiggler is $\Delta\gamma_{\parallel}/\gamma_{\parallel} \leq 0.003$ ($\gamma_{\parallel} = [1 - v_{\parallel}^2/c^2]^{-\frac{1}{2}}$).

The gun focusing coils guide the electron beam into a rectangular (1.01 cm \times 2.29 cm) stainless steel evacuated drift tube which is also the waveguide for the electromagnetic radiation. The beam is contained by a uniform axial magnetic field $B_{\parallel} \approx 1.6$ kG. The beam current entering the magnetic wiggler is in the range of 1-5 A. The 65 period wiggler magnet has a periodicity $l_w = 3.5$ cm, a maximum amplitude $B_w = 1.0$ kG, and is generated by bifilar conductors. Since the beam aperture limits the size of the beam to

$r_b/l_w \approx 0.07$, the wiggler field is close to that of an ideal wiggler. That is, the effects of the radial variation of the wiggler field and the presence of the off-axis components are usually small. At the wiggler entrance a slowly increasing field amplitude is produced by resistively loading the first six periods of the wiggler magnet⁵, thereby providing an adiabatic entrance for the electrons.

The 2.7 m long drift tube acts as a rectangular waveguide whose fundamental TE_{10} mode has a cutoff frequency of 6.6 GHz. Microwaves are launched onto the electron beam by a waveguide coupler (see Fig. 1). All our measurements are carried out at frequencies between 7 and 11 GHz. At these frequencies the empty waveguide can support only the fundamental (TE_{10}) mode, all higher modes being evanescent.

Two monochromatic waves are injected into the system. One is a variable frequency wave ($7 \leq f \leq 11$ GHz) emanating from of a traveling wave tube (TWT) whose typical output powers are in the 1-10 W range. It is this low power wave which is being amplified at the proper⁵ resonant electron beam energy. The other is a non-resonant, perturbing wave obtained from a magnetron capable of providing up to 25 kW of RF power at a fixed frequency $f_0 = 9.31$ GHz. At the output end of the wiggler, a mica window transmits the linearly polarized radiations, where they are measured by means of standard calibrated crystal detectors.

A system of microwave filters placed at the output of the FEL (see Fig. 1) insures that none of the high power radiation of frequency f_0 reaches the crystal detectors assigned to measure the FEL gain and phase at frequency f (the discrimination is better than 65 dB).

In order to determine the growth rate $\Gamma = (1/P)dP/dz$ of the wave, the output power $P(z)$ is measured as a function of the length of the interaction region. This is accomplished by means of an axially movable horse-shoe "kicker" magnet that deflects the electron beam into the waveguide wall at any desired position z , thereby terminating the interaction at that point. The measurement is illustrated in Fig. 2a for the case when the perturbing magnetron signal P_0 at frequency f_0 is off, and when it is turned on with an input magnitude given by $P_0 = 7.8$ kW, and $f_0 = 9.31$ GHz. We see that as a result of the perturbing wave, the total FEL gain (P_{out}/P_{in}) drops from 13.6 dB to 7.8 dB. The corresponding small signal growth rate Γ derived from Fig. 2a falls from 8.4 dB/m to 3.9 dB/m.

In addition to the intensity, we have also measured the RF phase of the electromagnetic wave. This is accomplished by standard interferometric techniques^{5,6} in which the antenna signal is mixed in a "magic tee" with a reference signal from the TWT launcher. Fig. 2b illustrates the relative phase as a function of z , both with the perturbing magnetron signal off and on. We note that in the collective (Raman) regime of this experiment the maximum phase change of the wave occurs⁵ near unity gain ($P_{out}/P_{in} \approx 1$), and it is at this point where all phase measurements shown in Fig. 2b and in subsequent figures were made.

One expects that the changes in the gain and phase are likely to be strong functions of both the perturbing magnetron input power P_0 , and its frequency f_0 relative to the FEL frequency f . Variations with P_0 are illustrated in Fig. 3, and variations with f are shown in Fig. 4. In both figures the ratio R is defined as the FEL output power with the magnetron on, to the FEL output power with the magnetron off. The phase $\Delta\Phi$ is the difference between the phases with magnetron on and off. We see that the detrimental effects on both the gain and the phase are most pronounced at high input powers P_0 and small frequency differences $|f - f_0|$.

In conclusion, we have presented what we believe are the first measurements of multi-frequency effects in a free electron laser amplifier. The observed changes in the gain and phase indicate that both the real and imaginary parts of the FEL dispersion characteristic are affected by the perturbing wave. Theoretical nonlinear wave particle studies are in progress to explain the observations.

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FIGURE CAPTIONS

Figure 1 Schematic of the experimental arrangement used in the study of FEL multi-frequency effects.

Figure 2 The FEL gain and phase in the presence and absence of the perturbing magnetron signal. $P_{in}(TWT)=1.5$ W; $f=9.90$ GHz; $P_0(\text{magnetron})=7.8$ kW; $f_0=9.31$ GHz; $V\approx 162$ kV; $I=1$ A; $B_{\parallel}=1580$ G; $B_w=132$ G.

Figure 3 FEL intensity and phase as a function of the input power of the perturbing magnetron signal of frequency, $f_0=9.31$ GHz; $P(TWT) = 6.8$ W; $f=9.7$ GHz; $V\approx 160$ kV; $I=1$ A; $B_{\parallel}=1580$ GHz; $B_w=100$ G.

Figure 4 FEL intensity and phase as a function of the FEL frequency f . $P_{in}(\text{magnetron})=2$ kW; $f_0= 9.31$ GHz; $P(TWT)\approx 7$ W; $V\sim 160$ kV; $I=1$ A; $B_{\parallel}=1580$ G; $B_w=100$ G.

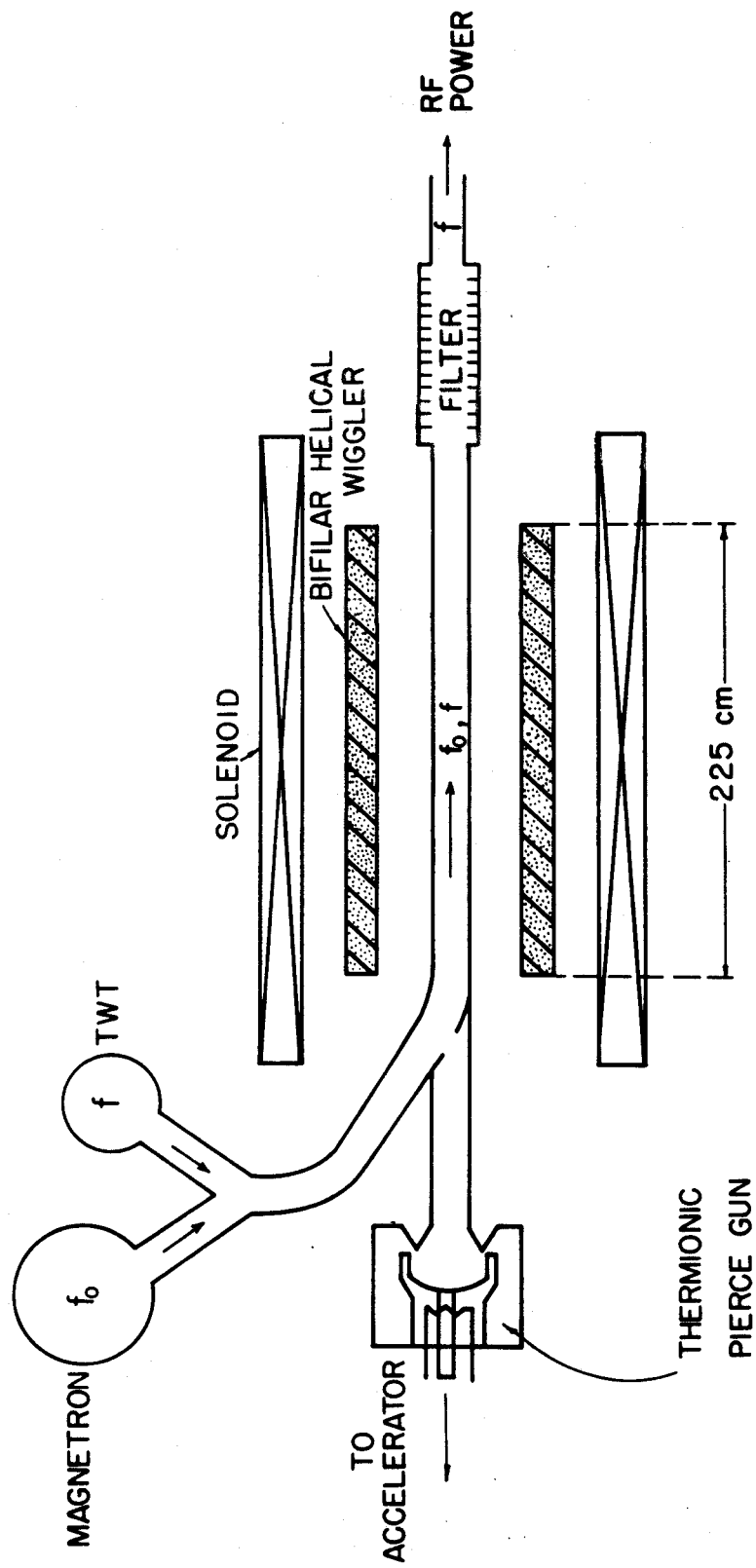
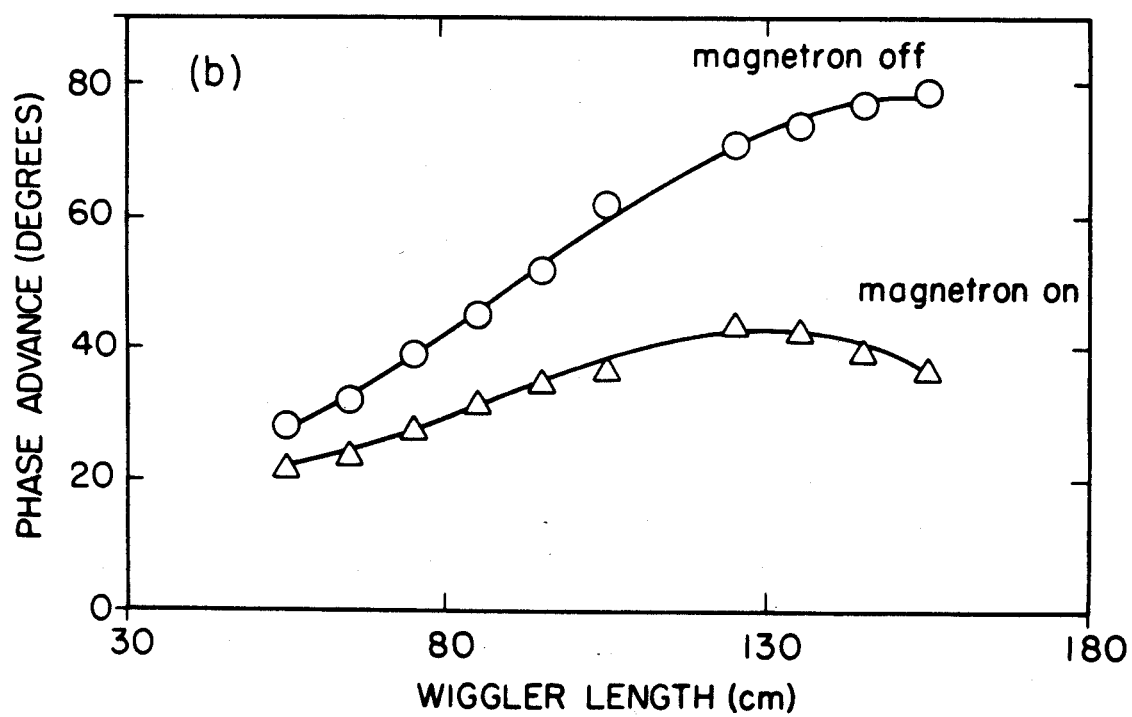
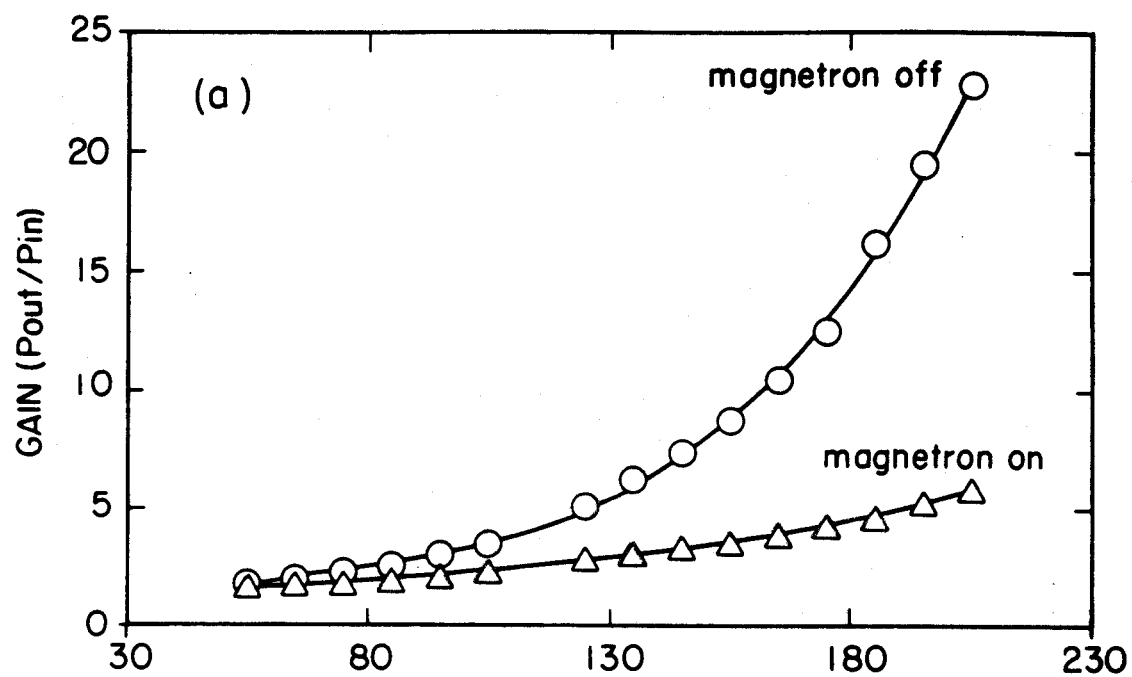


Fig. 1. Xu and Bekefi



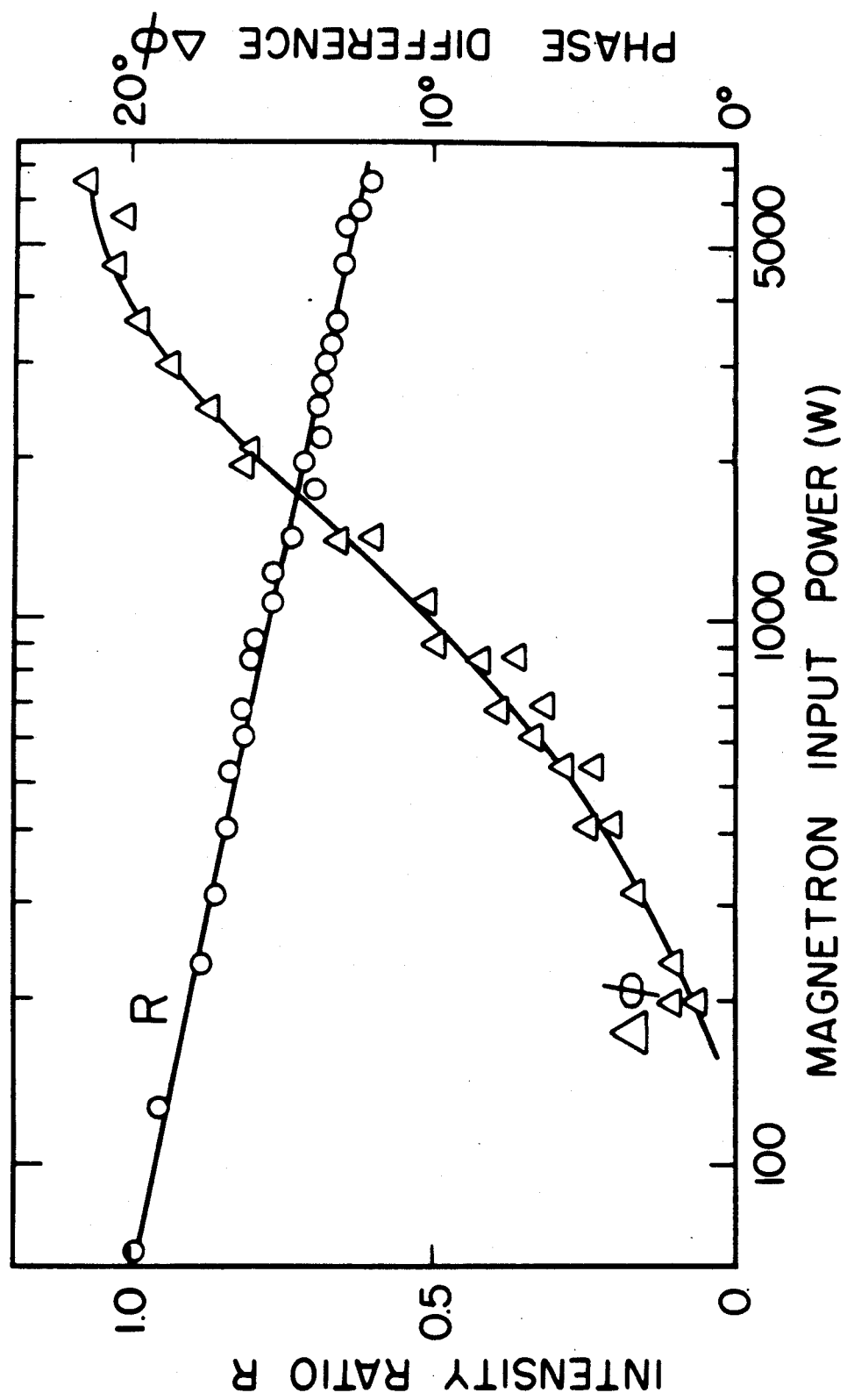


Fig. 3. Xu and Bekefi

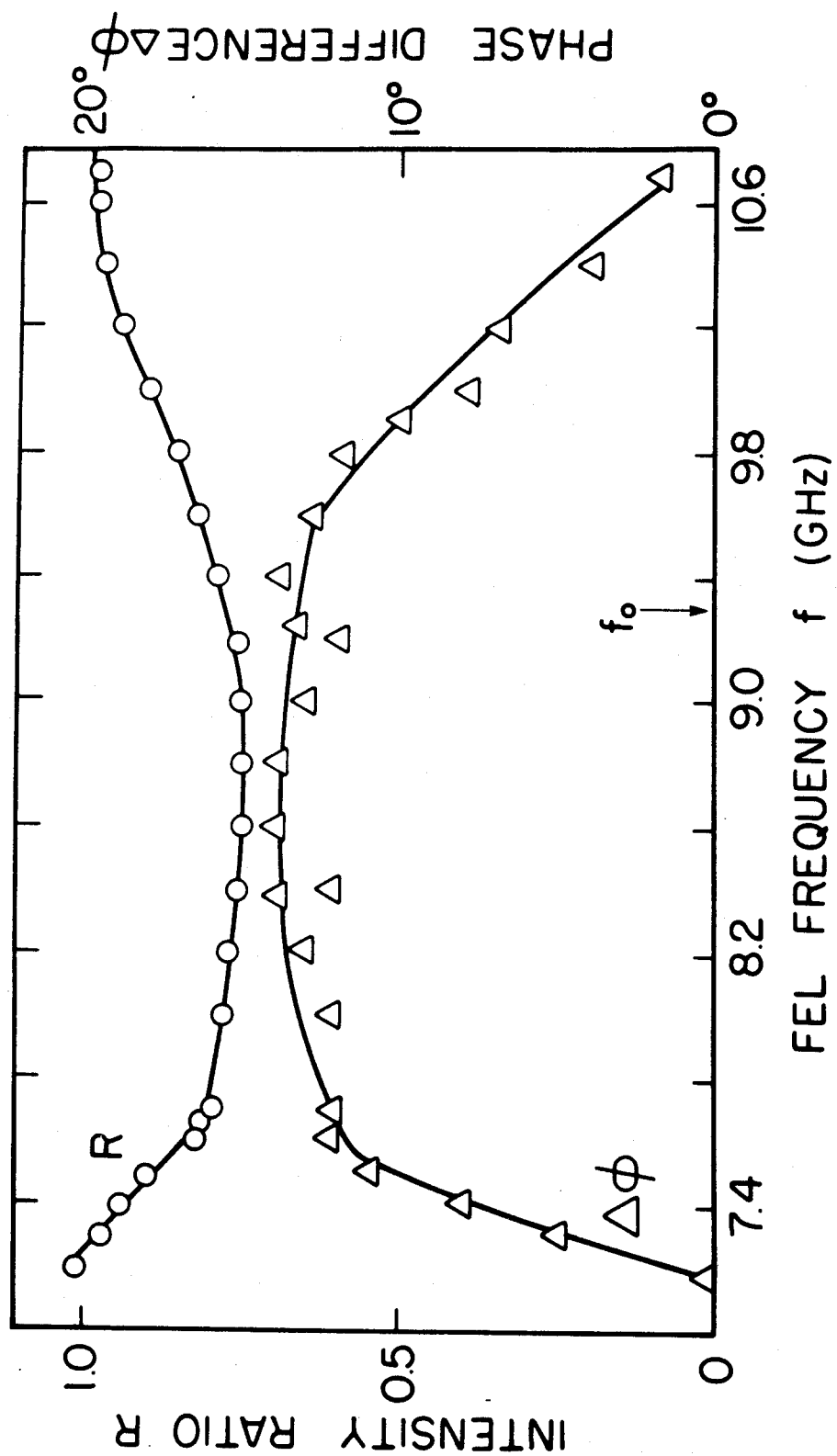


Fig. 4. Xu and Bekefi