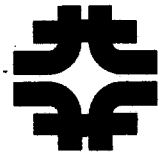


Fermilab

$\bar{p}$ Note #413

Restrictions on TWT Helix Voltage Ripple For Acceptable Notch Filter Performance

B. Hyslop

12/1/84

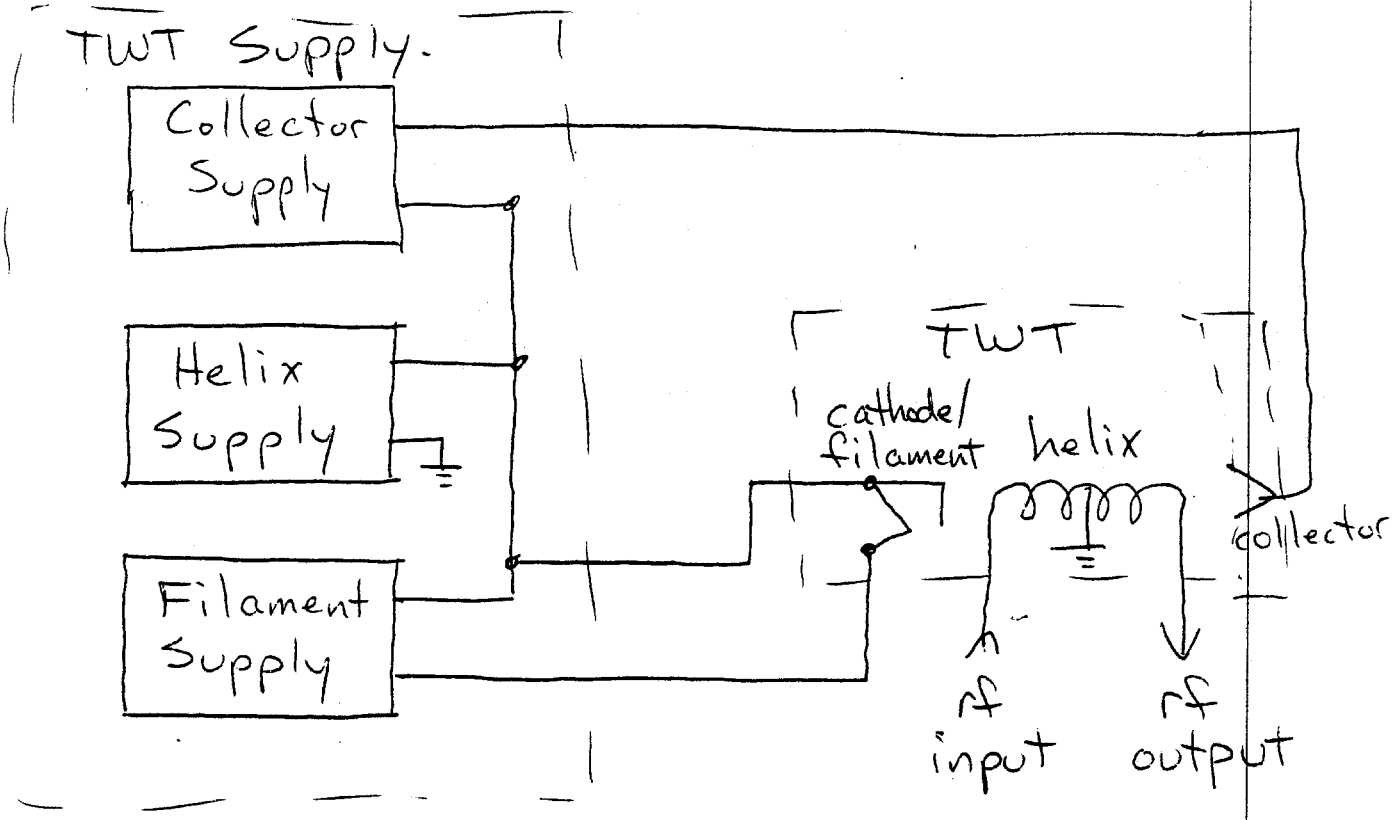
P-Note 413

12/1/84
Hyslop

Restrictions on TWT Helix Voltage Ripple for Acceptable Notch Filter Performance

Brian Hyslop

Summary: An ac ripple on the helix voltage of the 1-2 GHz TWT's creates FM sidebands that cause amplitude & phase modulation of the microwave TWT output signal. A limit of ~~eight~~ 16 volts peak-to-peak is required for acceptable superconducting notch filter performance.



TWT Structure Diagram

A variation in helix voltage will modulate the electron beam emitted from the cathode of the TWT.

This note calculates the effects ~~&~~ an ac ripple on the ~~dc~~ helix voltage ~~and~~ will have on TWT and superconducting notch filter.

A change in ~~gr~~ helix voltage will cause a change in rf group delay.

For the 1-2 GHz tubes used in the superconducting notch filter,

$$\alpha_{12} = \frac{\text{the change in group delay}}{\text{change in helix voltage}}$$

$$= 1 \text{ psec/volt.}$$

~~These~~ This slope was obtained by ~~calculating~~ measuring the group delay at five different helix voltages with a constant ~~of~~ TWT rf output power.

Let $V_{helix} = V_{dc} + V_o \sin \omega_m t$ where:

V_{dc} = the nominal helix voltage setting

V_o = the magnitude of the ac ripple

ω_m = ~~the frequen~~ $2\pi *$ the modulating frequency of the ac ripple.

Let $\Delta\tau_g$ = the change in group delay due to the helix voltage ac ripple.

$\Delta\tau_g = \alpha V_o \sin \omega_m t$ where α = the conversion factor between group delay and helix voltage.

For an unmodulated helix voltage, let the single-tone rf output of the tube = $x_c(t)$.

$x_c(t) = A_c \cos \omega_c t$.

When modulated by the helix voltage ripple, the carrier output =

$$x_c(t) = A_c \cos(\omega_c(t + \Delta\tau_g))$$

$$= A_c \cos\left(\omega_c t + \frac{2\pi\alpha V_0}{T} \sin\omega_m t\right)$$

where $T = \frac{1}{f_c}$

From FM theory, $\frac{2\pi\alpha V_0}{T} = \beta$ = the modulation index. Again, from FM theory,

$$x_c(t) = A_c \sum_{n=-\infty}^{\infty} J_n(\beta) \cos(\omega_c + n\omega_m)t$$

where $J_n(\beta)$ = the n^{th} order Bessel function.

For $\beta = 0$, $J_0(\beta) = 1$ and all of the ~~power is in~~ rf power is in the main lobe.

For $\beta \neq 0$, ~~rf~~ po sidebands from the main lobe contain some of the rf power. The power reduction in the main lobe for $\beta \neq 0$ = ~~A_c~~

$$10 \log\left(\frac{A_c^2 J_0^2(\beta)}{A_c^2 J_0^2(0)}\right) = 20 \log J_0(\beta)$$

From $\beta = \frac{2\pi \alpha V_0}{T}$, one sees:

a) β increases linearly with the rf carrier frequency. For the 1-2 GHz tubes, β_{max} occurs at $f_c = 2$ GHz.

b) β is proportional to the

amplitude of the helix voltage ripple.

Sample calculation:

Let $V_0 = 7.9V$, $f_c = 2GHz$, and $\alpha = 1 psec/V$.

$$\beta = 2\pi\alpha V_0 f_c = .1$$

$$J_1^2(\beta) = (.05)^2 = 2.5 * 10^{-3}$$

Thus, the first FM sideband for this case would have an amplitude relative to the carrier of $10 \log\left(\frac{J_1^2(.1)}{J_0^2(.1)}\right)$

~~$= 10 \log\left(\left(\frac{.05}{.9975}\right)^2\right) = -26 dB.$~~

$$= 10 \log\left(\left(\frac{.05}{.9975}\right)^2\right) = -26 dB$$

Measurements were made on the rf output of a Varian TWT due to helix voltage modulation.

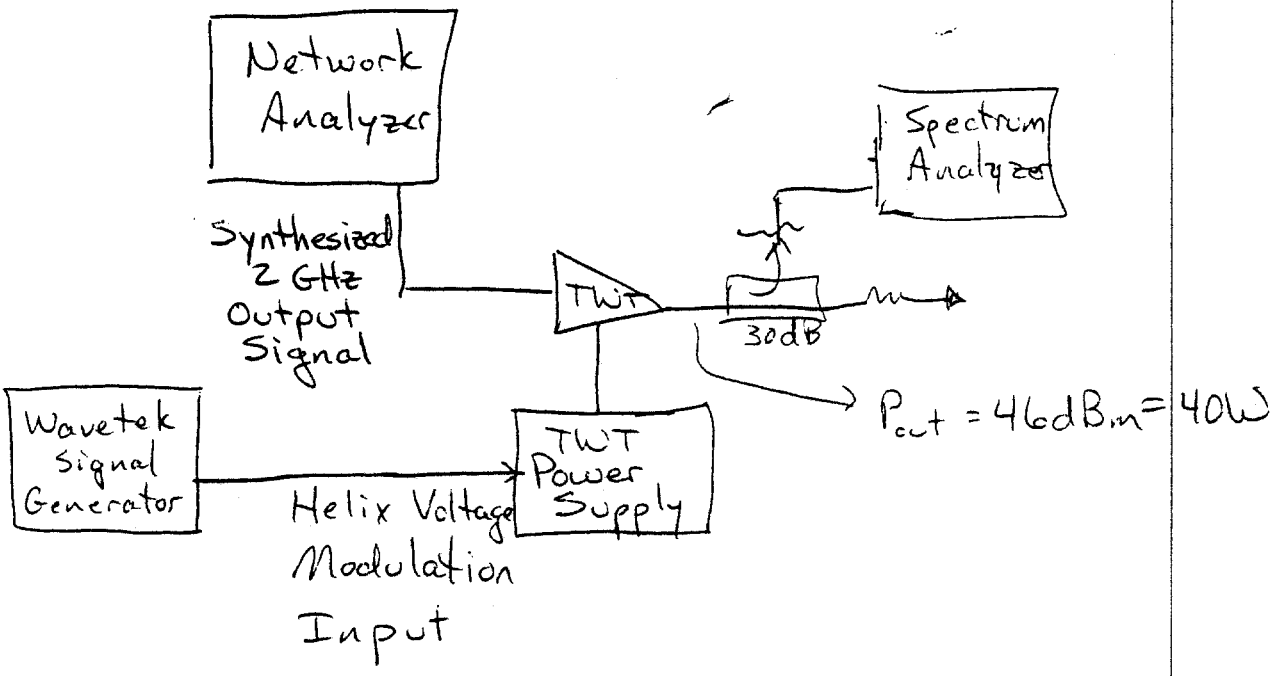


Fig. 1 : Test Setup

Figure 2 shows the network analyzer input signal to the TWT.

Figure 3 shows the TWT rf output with zero volts - helix modulation.

Figure 4 shows a series of measurements of the TWT output signal with a 15V peak-to-peak helix voltage modulation input signal. The measurements were made at a modulating frequency f_m = 1kHz, 20kHz, and 50kHz.

~~For f_m = 1kHz, the first sideband is 23 dB below the carrier. At f_m = 20kHz, the~~

f_m (modulating frequency)	Sideband amplitude (dB below carrier)
1 kHz	23.7
20 kHz	25.8
50 kHz	29.3

~~The variation in amp~~

The dependence of the sideband amplitude on the modulating frequency can be attributed to the 3 dB point of the helix voltage modulation input which ~~was~~ is at 50 kHz.

~~Measurements~~

These measurements agree with the predicted value of 26 dB for a V_0 of 7.9 V from the example.

Figure 2: Network Analyzer Output at 2GHz

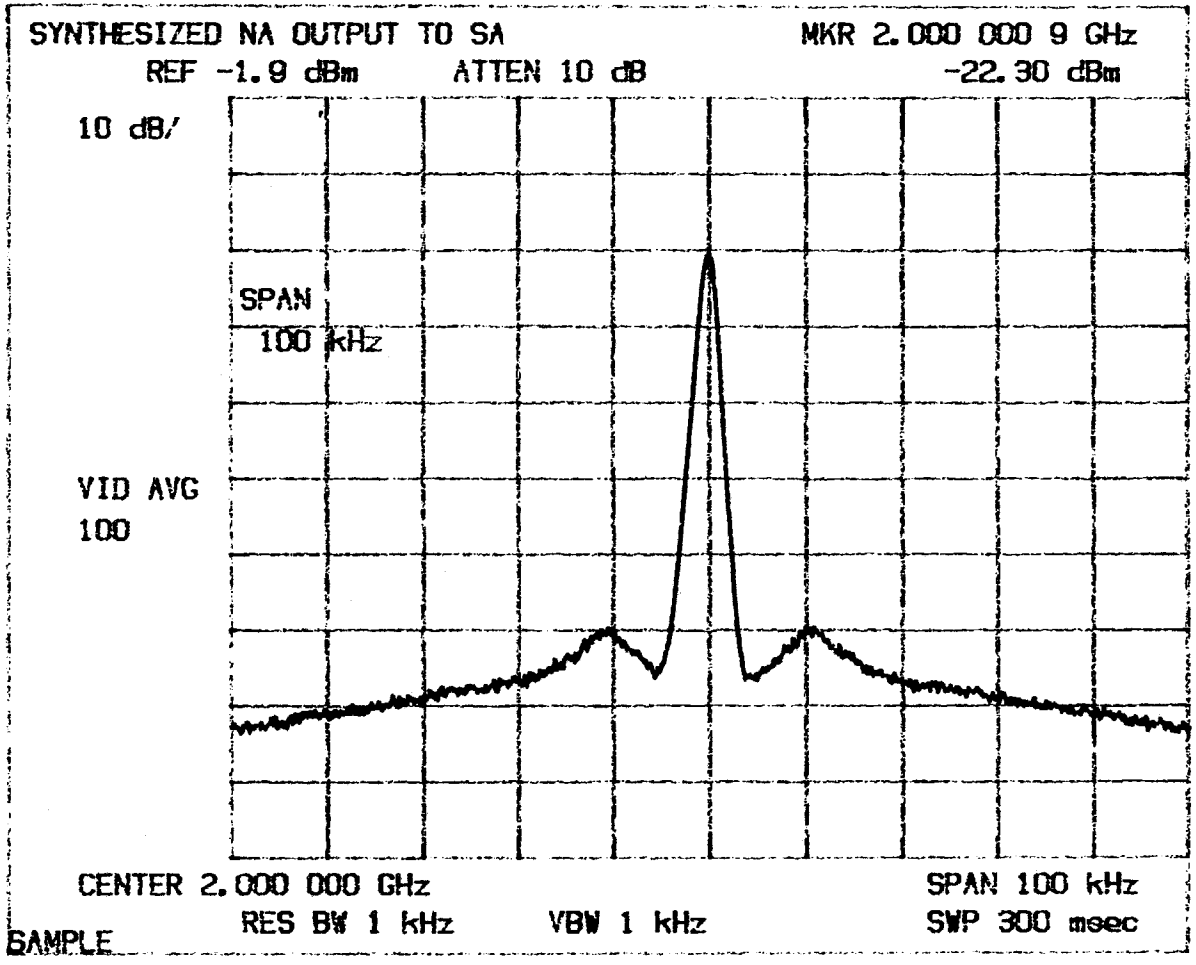
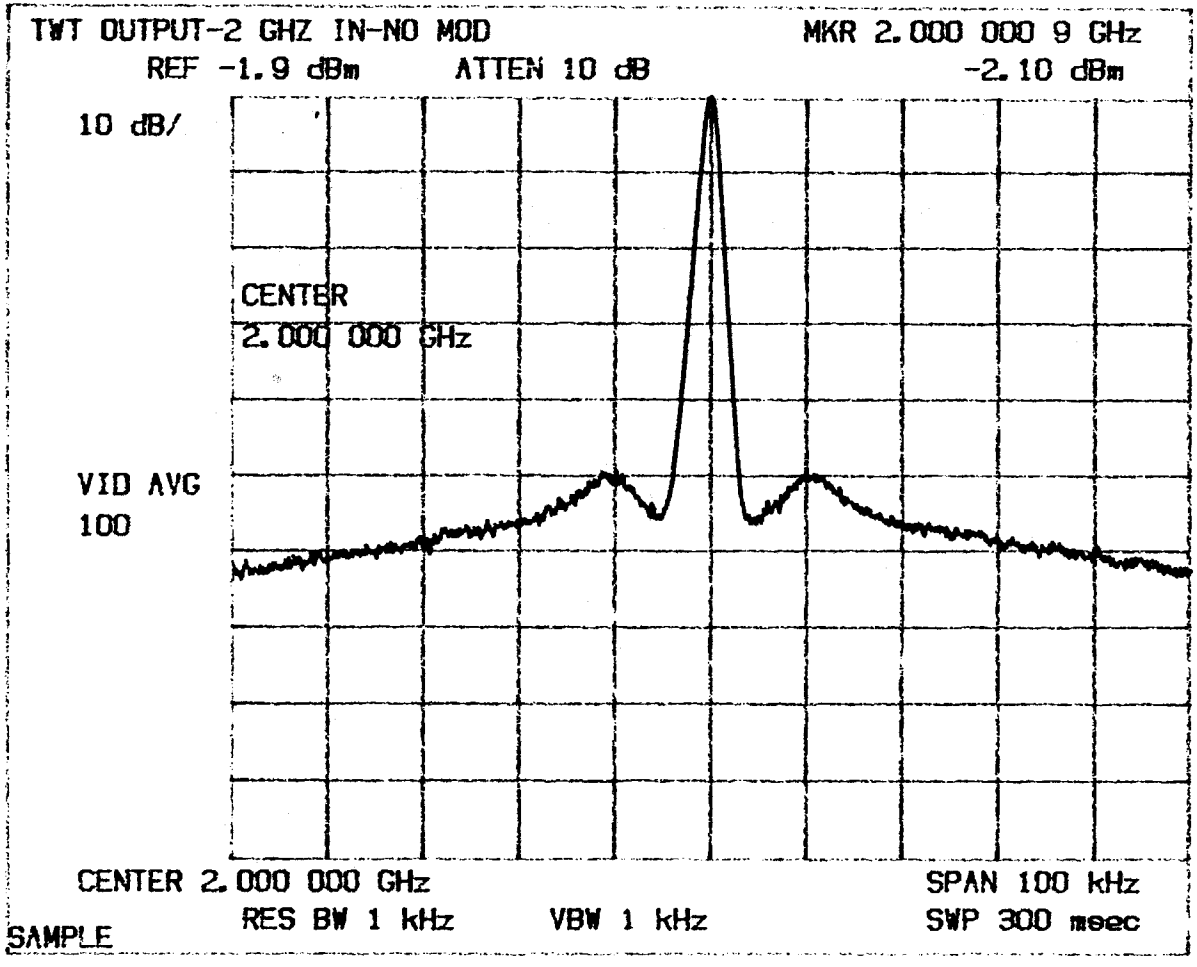
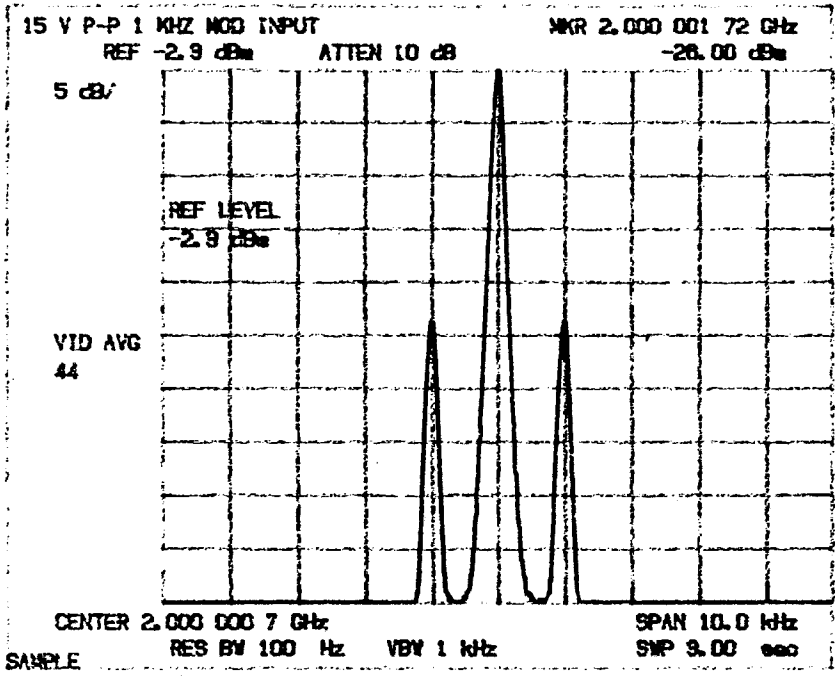
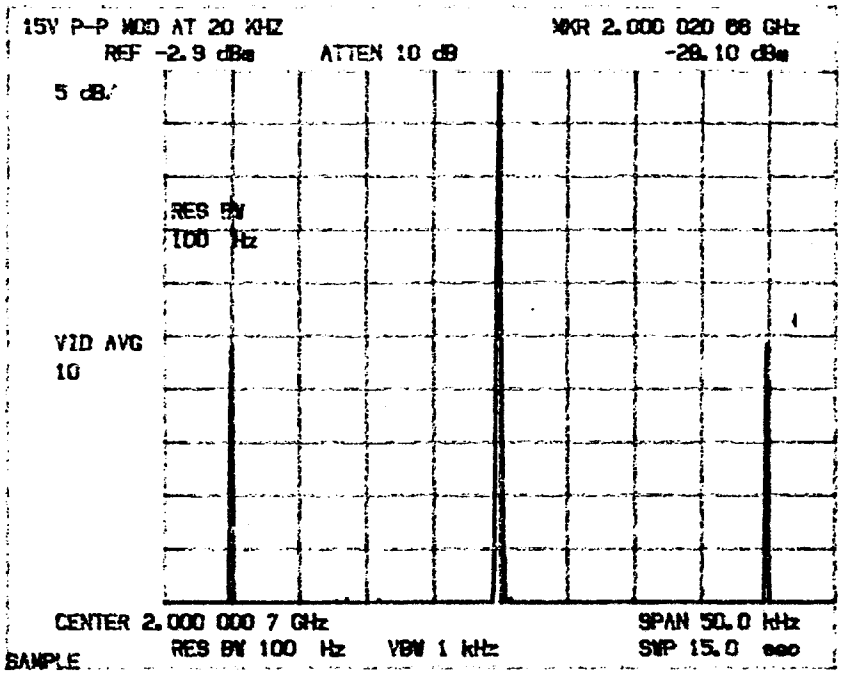
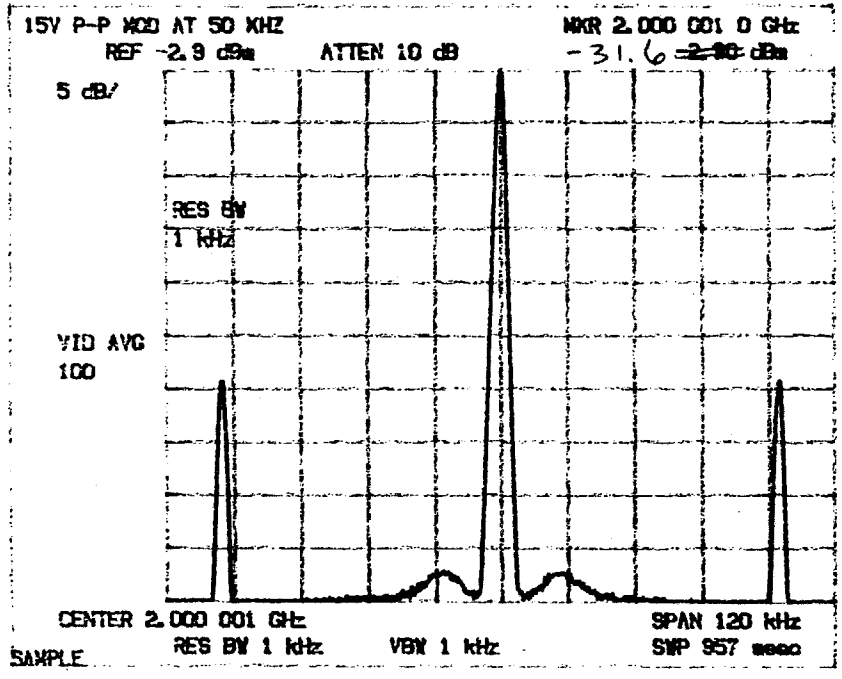


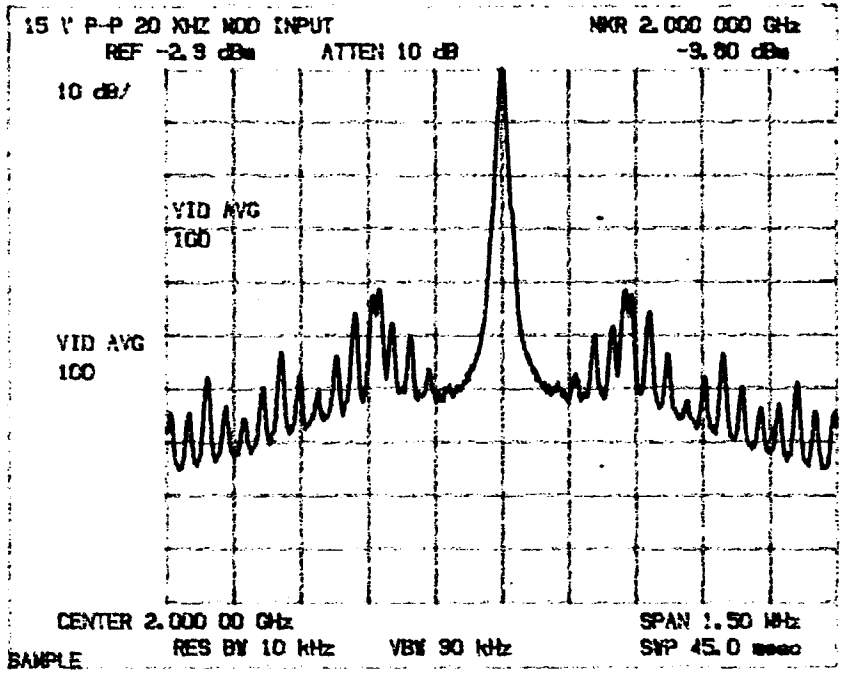
Fig. 3- TWT rf output from 2GHz Network Analyzer input signal



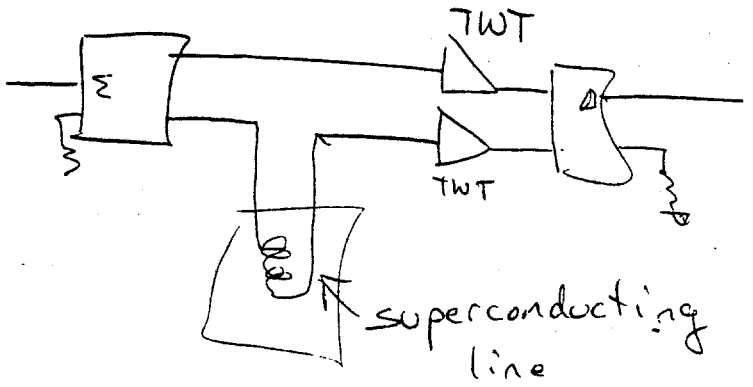

15 V P-P 1 KHZ MOD INPUT
MKR 2.000 001 72 GHz
REF -2.9 dBm
ATTEN 10 dB
-28.00 dBm
5 dB/
REF LEVEL
-2.9 dBm
VID AVG
44
CENTER 2.000 000 7 GHz
SPAN 10.0 kHz
RES BW 100 Hz
VBW 1 kHz
SWP 9.00 sec
SAMPLE


15V P-P MOD AT 20 KHZ
MKR 2.000 020 68 GHz
REF -2.9 dBm
ATTEN 10 dB
-28.10 dBm
5 dB/
RES BW
100 Hz
VID AVG
10
CENTER 2.000 000 7 GHz
SPAN 50.0 kHz
RES BW 100 Hz
VBW 1 kHz
SWP 15.0 sec
SAMPLE


15V P-P MOD AT 50 KHZ
MKR 2.000 001 0 GHz
REF -2.9 dBm
ATTEN 10 dB
-31.6
5 dB/
RES BW
1 KHz
VID AVG
100
CENTER 2.000 001 GHz
SPAN 120 kHz
RES BW 1 kHz
VBW 1 kHz
SWP 957 msec
SAMPLE


15 V P-P 20 KHZ MOD INPUT
MKR 2.000 000 GHz
REF -2.9 dBm
ATTEN 10 dB
-9.80 dBm
10 dB/
VID AVG
100
VID AVG
100
CENTER 2.000 00 GHz
SPAN 1.50 MHz
RES BW 10 kHz
VBW 90 kHz
SWP 45.0 msec
SAMPLE

II) Effects of helix voltage ripple ~~modes~~ on the superconducting notch filter.



The notch filter has a transfer function proportional to $(1 - m\cos(2\pi f T_o))$ where T_o = 1.59 μsec = the period of the Accumulator, and m = the ~~mismatch flaw~~ amplitude mismatch between the two legs.

The effects of the helix voltage ripple on notch filter performance can be split into three categories:

1) To attain notches 30dB deep or greater, the two legs of the filter must be matched to ±.5dB or better.

Consider the case where one TWT has a helix voltage ripple and the second TWT does not.

The amplitude mismatch between the two legs = $10\log \frac{J_0^2(\beta)}{J_0^2(0)} = 20\log J_0(\beta)$.

Thus, $20\log J_0(\beta) \geq -.5dB$

$$J_0(\beta) \geq 10^{-.01} = .977$$

$$.977 \doteq J_0(.3) = .9775$$

For $\beta = .3$, $V_0 = \frac{\beta}{2\pi f \alpha} = 23.9V$

Thus, the ac peak-to-peak voltage ripple allowed in one tube = $2V_0 = 48V$.

2) The phase modulation due to the FM sidebands must be small enough to maintain a filter dispersion spec of ±5ppm.

$$|\delta| \leq 5\text{ppm} = \frac{f_H - Hf_0}{Hf_0} \quad \text{where}$$

H = the harmonic number, f_H = the measured notch frequency, & f_0 = the fundamental filter frequency.

The smallest frequency deviation for $|\delta|$ occurs at $Hf_0 = 1\,GHz$ for a 1-2 GHz filter.

Let $f_H = Hf_0 + \Delta f$

$$\frac{\Delta f}{Hf_0} = \frac{\Delta f}{1GHz} \leq 5 * 10^{-6}$$

$$\Delta f \leq 5\,kHz.$$

The corresponding phase shift = $\Delta\phi = 360\left(\frac{5\text{kHz}}{629.9\text{kHz}}\right) = 2.86°$.

where $f_o = \frac{629.9\text{kHz}}{}$ = 1/(1.59 μsec).

Previously, the expression

$$x_c(t) = A_c \sum_{n=-\infty}^{\infty} J_n(\beta)\cos(\omega_c + n\omega_m)t +$$

was derived for an FM-modulated signal.

~~$x_c(t)$ If one assumes~~

For narrowband FM modulation,

$$x_c(t) = A_c J_0(\beta)\cos\omega_c t + A_c J_1(\beta)\cos(\omega_c+\omega_m)t +$$

$$* - A_c J_1(\beta)\cos(\omega_c - \Delta\omega_m)t +$$

$$= A_c J_0(\beta)\cos\omega_c t - 2J_1(\beta)\sin\omega_c t \sin\omega_m$$

The phase shift in the resultant carrier signal = $\tan^{-1}\left[\frac{-2J_1(\beta)\sin\omega_m t}{J_0(\beta)}\right]$

Let ϕ_{max} = the peak phase shift allowed for a ±5 ppm dispersion measurement.

$$\phi_{max} = 2.86° \geq \tan^{-1}\left(-2J_1(\beta)\sin\omega_m t / J_0(\beta)\right)$$

$$\tan(2.86°) = .05$$

$$-2J_1(\beta)\sin\omega_m t / J_0(\beta) \leq .05$$

For β small, $J_\nu(\beta) \doteq (\frac{1}{2}\beta)^\nu / \nu!$

$$J_0(\beta) \doteq 1$$

$$J_1(\beta) \doteq \beta/2$$

~~$J_1(\beta) \doteq .05$~~

$$\beta \cdot \frac{-2J_1(\beta)\sin\omega_m t}{J_0(\beta)} \doteq -\beta\sin\omega_m t \leq .05$$

For $\sin\omega_m t = -1$, $\beta_{max} = .05$

$$\beta_{max} = 2\pi \cdot \alpha V_0 f_c \Rightarrow V_0 = \frac{.05(\frac{1000}{\cancel{500}\text{psec}})}{2\pi(1\text{psec}/\text{volt})} = 8\text{V}.$$

Thus, $V_{ac} = 2V_0 = 16$ Volts peak-to-peak.

3) ~~Sidebands from~~ FM sidebands from ~~an~~ rf power at a frequency close to a notch must not fill the notch of the filter.

The ~~a~~ transfer function of ~~a~~ a superconducting notch filter $= 10\log(1 - m\cos(2\pi f/f_0))^2$

where m = the filter amplitude mismatch
($m=1$ gives infinitely deep notches)
& f_0 = the filter's fundamental freq.

For a filter notch of -30 dB,

$$20\log(1-m) = -30\text{dB}$$

$$m = .97$$

The switching frequency of the helix voltage supply = 20kHz.

The amplitude of the notch filter Transfer function 20kHz away from a notch equals A =

$$A = 20\log(1-.97\cos(2\pi(\tfrac{20}{629.9})))$$

$$A = -26\,dB = 20\log(1-.97(.98))$$

Earlier, I showed that a 14Vac ripple gave a sideband power 26 dB below the main carrier.

~~For a notch filter to have an equal power co~~

~~Also~~ ~~Flso~~ Thus, the first sideband would have to be 4 dB below the carrier to fill a 30 dB notch.

Assume a 14 V helix voltage peak-to-peak ripple exists on a TWT with a frequency of 20kHz.

The first sideband is 26dB below the carrier ~~and is~~ for this case.

One can calculate the notch minimum for which the sideband will begin to fill the notch by

$$10\log\left(\frac{1-m\left(\cos 2\pi \frac{20}{629.9}\right)}{1-m}\right)^2$$

$$= 20\log\left(\frac{1-m(.98)}{1-m}\right) \geq 26dB$$

$$m = .9989$$

The corresponding notch depth =

$$10\log(1-(.9989))^2 = 59.6dB.$$

Conclusion:

~~Ac~~ AC ripple on the helix voltage supply ~~can~~ creates FM sidebands on the TWT rf output.

Assuming an otherwise perffectly matched notch filter, the peak-to-peak ac ripple would need to be limited to 16 Volts in order to meet the notch filter dispersion spec of ± 5 ppm.