Fermilab

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Restrictions on TWT Helix Voltage Ripple
For Acceptable Notch Filter Performance

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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 ¹⁶~~eight~~ 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 of an ac ripple on the ~~the~~ helix voltage and will have on TWT and superconducting notch filter performance.

A change in ~~of~~ 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 $V_{\text{helix}} = V_{\text{dc}} + V_0 \sin \omega_m t$ where:

V_{dc} = the nominal helix voltage setting

V_0 = the magnitude of the ac ripple

$\omega_m = \text{the frequency } 2\pi \times \text{the modulating frequency of the ac ripple.}$

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

$\Delta \tau_g = \alpha V_0 \sin \omega_m t$ where α = the conversion factor between group delay and helix voltage.

For an unmodulated helix

voltage, let the ~~rf~~ 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 =

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

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

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

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~~ 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, $\beta_{\max}$ occurs at $f_c = 2 \text{ GHz}$.

b) β is proportional to the

amplitude of the helix voltage ripple.

Sample calculation:

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

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

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

Thus, the first FM sideband for this case would have an amplitude relative to the carrier of

$$10 \log \left(\frac{J_1^2(.1)}{J_0^2(.1)} \right)$$

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

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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 $f_m = 1\text{ kHz}$, 20 kHz , and 50 kHz .

~~For $f_m = 1\text{ kHz}$, the first sideband is 23 dB below the carrier. At $f_m = 20\text{ kHz}$, 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

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

The notch filter has a transfer function proportional to $(1 - m \cos(2\pi f T_0))$ where $T_0 = 1.59 \mu\text{sec}$ = the period of the Accumulator, and m = the ~~mismatch~~ ~~for~~ 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 ~~a~~ notches 30dB , deep or greater, the two legs of the filter must be matched to $\pm .5\text{dB}$ 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, $20 \log J_0(\beta) ~~-35\text{dB}~~ \geq -.5\text{dB}$

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

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

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

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

2) The phase modulation due to the FM sidebands must be small enough to maintain a filter dispersion spec of $\pm 5 \text{ ppm}$.

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

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

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

$$\text{Let } f_H = Hf_0 + \Delta f$$

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

$$\Delta f \leq 5 \text{ kHz.}$$

The corresponding phase shift = $\Delta\phi = 360 \left(\frac{5 \text{ kHz}}{629.9 \text{ kHz}} \right) = 2.86^\circ$
 where $f_o = \frac{629.9 \text{ kHz}}{1/(1.59 \mu\text{sec})}$.

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,

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

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

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

Let $\phi_{\max}$ = The peak phase shift allowed for a ± 5 ppm dispersion measurement.

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

$$\tan(2.86^\circ) = .05$$

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

$$\text{For } \beta \text{ small, } J_0(\beta) \doteq (\frac{1}{2}\beta)^0 / 0!$$

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

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

$$\cancel{J_1(\beta)} \doteq .05$$

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

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

$$\beta_{\max} = 2\pi \times V_0 f_c \Rightarrow V_0 = \frac{.05 \left(\frac{1000}{500} \text{ psec} \right)}{2\pi (1 \text{ psec} \times \text{volt})} = 8V$$

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 ~~pr~~ transfer function of
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 = 20 kHz.

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

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

$$A = -26 \text{ dB} = 20 \log(1 - .97(.98))$$

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

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

~~One~~ ~~Then~~ 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 20 kHz.

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

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

$$10 \log \left(\frac{1 - m \left(\cos 2\pi \frac{20}{629.9} \right)}{1 - m} \right)^2$$
$$= 20 \log \left(\frac{1 - m(.98)}{1 - m} \right) \geq 26 \text{ dB}$$

$$m = .9989$$

The corresponding notch depth =

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

Conclusion:

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

Assuming an otherwise perfectly 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 $\pm 5 \text{ ppm}$.