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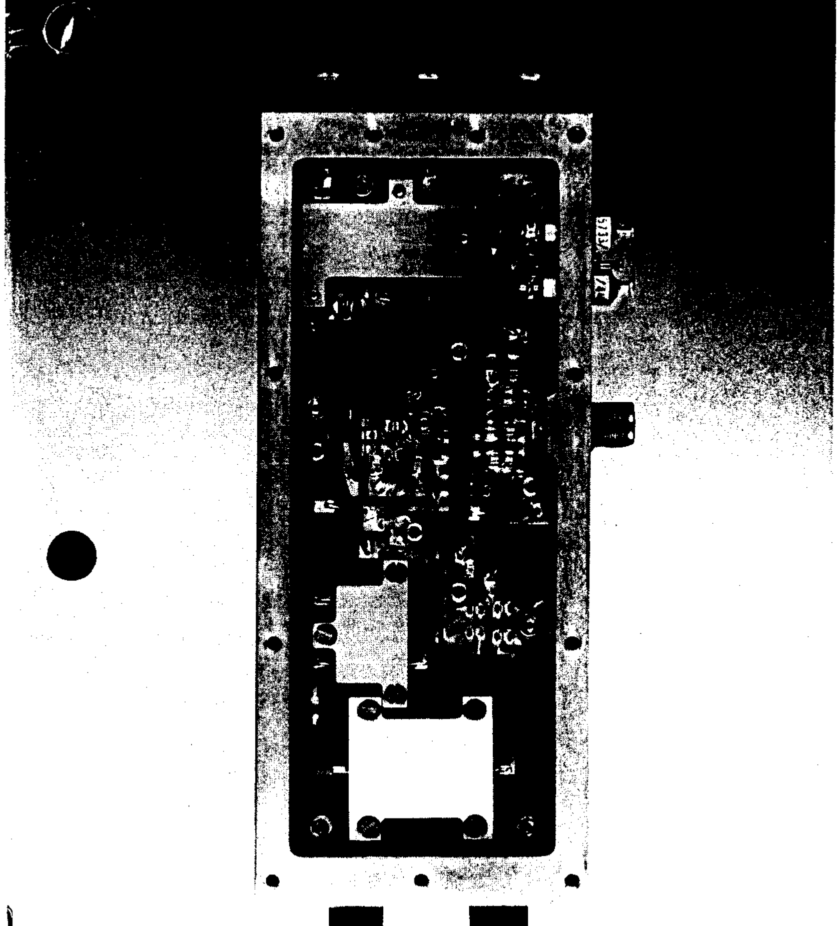
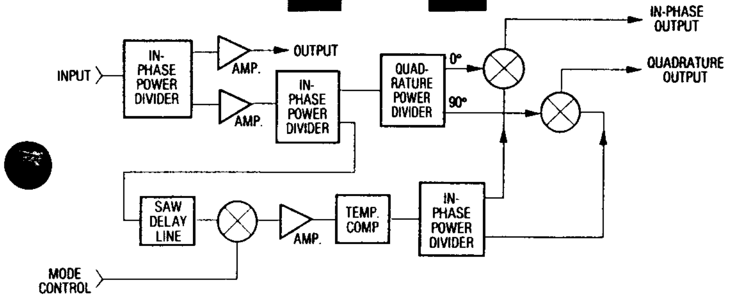
Frequency Discriminators





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This article provides an introduction to frequency discriminators, sometimes simply called discriminators. After explaining the basic structure and applications of a discriminator, the theory of operation is discussed. A few specific examples of discriminators are then provided.

Introduction

A frequency discriminator is a device that provides an output voltage whose value is a function of the instantaneous frequency of the input signal (see Figure 1).

There are several discriminator applications in microwave and rf systems and subsystems. In one application, a discriminator is used in a phase-locked loop to provide a very stable rf source. The discriminator is designed to have an output voltage which approximates a monotonic linear function of the instantaneous input frequency over a limited bandwidth, and which produces zero volts at the desired center frequency. The dc output of this type of discriminator is an error voltage proportional to the difference between the actual frequency of the output and the desired frequency. By feeding this error voltage back to the input of the voltage-variable-frequency source (see Figure 2), a phase-locked loop is obtained. This circuit corrects for any frequency drift and provides a very stable and accurate output.

Discriminators are also used for instantaneous frequency measurements (IFM), quickly and accurately identifying instantaneous signal frequencies in applications that require a high probability-of-intercept (5).

Theory of Operation

The three main components of a discriminator are the power-splitting network, the delay line, and the phase discriminator. The power-splitting network provides a reference signal and a test signal. The delay line adds a fixed time delay to the test signal. (A fixed time delay is mathematically equal to a phase shift which varies linearly with frequency.) Finally, the phase discriminator converts the phase difference between the reference signal and the delayed signal into the output voltage of the discriminator.

Power-Splitting Networks

Many types of power-splitting networks (both in-phase and quadrature) may be utilized in discriminators. A few examples are discussed below.

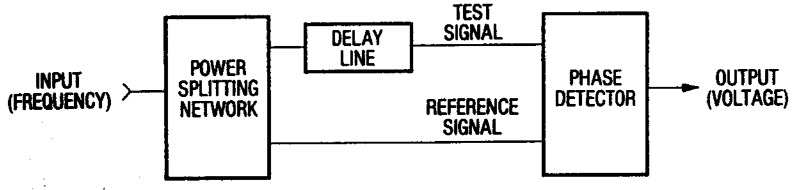


Figure 1. Basic frequency discriminator.

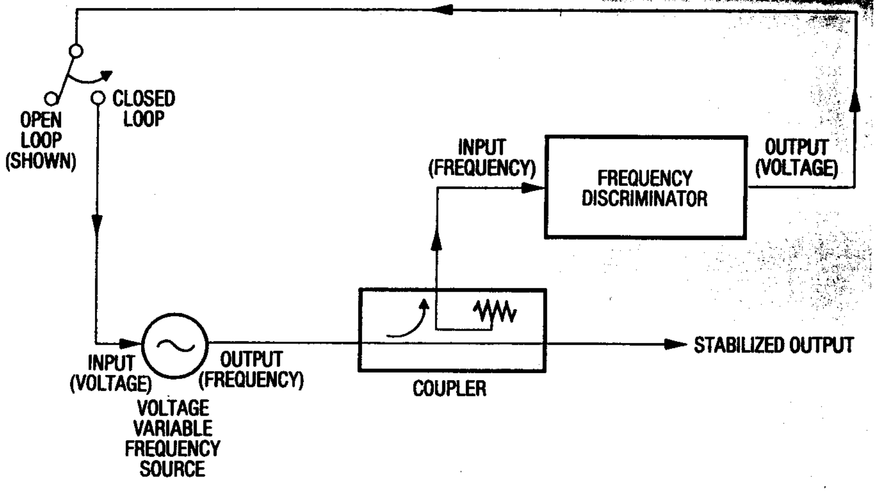


Figure 2. Discriminator stabilized oscillator.

A resistive in-phase power splitter (see Figure 3) is potentially very broadband, small, and inexpensive. However, the isolation between the two output ports is very poor (typically on the order of 7 dB), making this type of power splitter impractical for many applications.

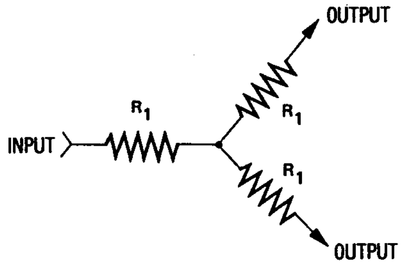
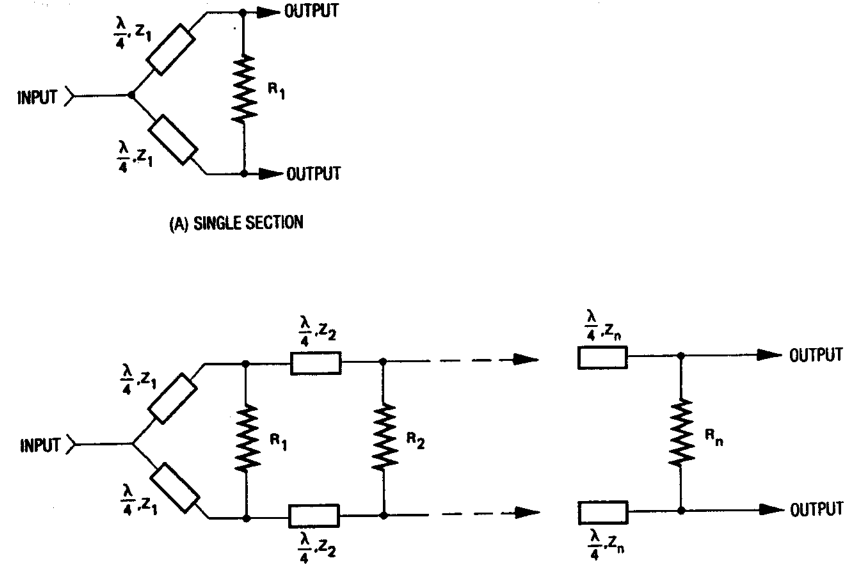


Figure 3. Resistive power splitter.

Wilkenson-style power splitters provide two in-phase outputs, and are constructed from quarter-wavelength lines and resistive terminations (see Figure 4). Wilkenson-style splitters provide better isolation than resistive power splitters, resulting in a relatively even power split, even with partially unmatched output impedances. Multisection Wilkenson-style splitters are much broader in bandwidth than the single-section Wilkenson-style splitters, but they require more space. All Wilkenson-style power splitters are very low in cost, because they can be printed directly onto a substrate.

Lange couplers (see Figure 5) are a form of power-splitting network which provides a 90° phase shift between its two output ports over a very broad bandwidth. They can be designed to provide approximately equal output levels over bandwidths of about 2:1 to 2.5:1. Lange couplers are often printed directly onto a substrate and can be connected to the rest of the circuit with microstrip lines.



(A) SINGLE SECTION

(B) MULTIPLE SECTION

Figure 4. Wilkenson-type power splitters.

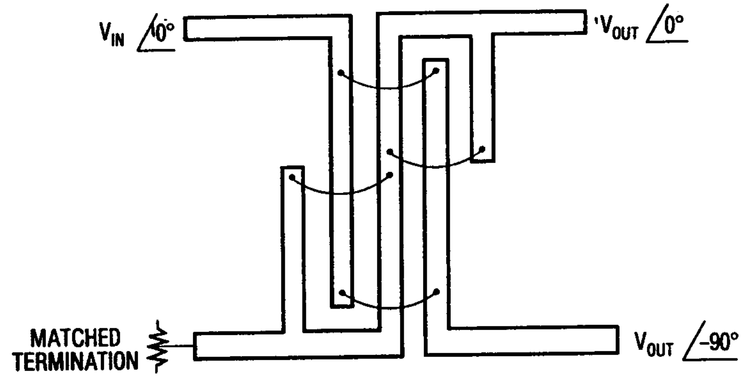


Figure 5. Lange coupler.

Lange couplers typically have narrow gaps and line widths, along with bonded connections, making them slightly more difficult to fabricate than Wilkenson-style power splitters.

Delay Line

For small delays (on the order of 10–100 nsec), a coaxial delay line is typically used. For larger delays at UHF frequencies and below, SAW delay lines or LC networks can be used. Larger delays are generally required when it is necessary to resolve a very small frequency increment.

Coaxial delay lines are simple, inexpensive, and can be used at microwave frequencies. A typical coaxial delay line will have a solid teflon dielectric material and a semirigid outer shell. Electrical characteristics include a measurable but small amount of dispersion, moderate loss (increasing with frequency), and a large variation in effective length with temperature (especially below +25°C). The variation in effective length with temperature will change the shape of the output-voltage versus input-frequency curve, often unacceptably.

There are several ways to minimize this variation in effective length with temperature. These include encapsulating the delay line in a thermally insulating material, placing a heater around the cable, using a series combination of delay lines with complementary temperature coefficients, and/or utilizing exotic dielectrics such as silicon dioxide or porous teflon. Cables utilizing a silicon dioxide dielectric offer superior performance over temperature, but are very expensive and few companies make them. Porous teflon dielectric cables generally offer both performance and cost between that of solid teflon and silicon dioxide.

SAW delay lines are basically broadband SAW filters. They can be used to implement delays from a few hundred nanoseconds to a few microseconds, with a bandwidth of up to 50%. SAW delay lines are typically usable within the frequency range of 20 MHz to 1 GHz, and are often used where coaxial delay lines would be too bulky.

While SAW delay lines are very small, they have several disadvantages, including moderate to high cost, typically dispersive characteristics, poor VSWR, and a very high insertion loss (typically 20–40 dB).

As a result of the above considerations, coaxial delay lines are generally used for delays of up to approximately 100 nsec, while SAW delay lines are used for larger delays where a coaxial delay line would be too large.

Phase Detector

The phase discriminator or phase detector produces an output voltage which varies with the phase difference between the two equal-frequency input signals. Typically, this variation is either linear or sinusoidal. Key phase-detector specifications include operating input power level, dc offset, peak voltage, phase-error ratio (the ratio of peak voltage to dc offset), and absolute output voltage for specified input phase differences.

A simple way to make a phase detector is to use a normal double-balanced mixer functioning as a time-domain "multiplier." Such a mixer will have two desired outputs, one at the sum frequency (2 x fo) and one at the difference frequency (dc). If a low-pass filter is used to eliminate the sum frequency, the output will be a dc voltage which varies sinusoidally with the phase difference between the inputs, as shown in Figures 6 and 7. There is a small por-

Calculation A:

First Input to Mixer $= V_1 = A\cos(\omega t)$

Second Input to Mixer $= V_2 = B\cos(\omega t + \theta)$

Mixer Output
$$= V_1 \cdot V_2$$
$$= AB\cos(\omega t)\cos(\omega t + \theta)$$
$$= \frac{AB}{2}\cos(2\,\omega t + \theta) + \frac{AB}{2}\cos(\theta)$$

where:
$$\frac{AB}{2}\cos(2\,\omega t + \theta) = \text{sum frequency at } 2\omega$$
$$\frac{AB}{2}\cos(\theta) = \text{difference frequency at dc}$$

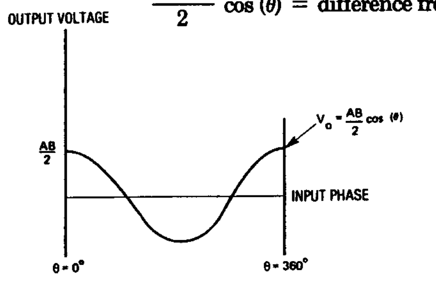


Figure 6. Derivation of output from mixer used as phase detector.

Calculation B:

Assumptions

(1) Diode conductivity is modulated by LO power, and varies digitally between 2 values, O and K.

(2) The duty cycle for diode conductivity is 50%

(3) $V_{RF} = A\cos(\omega t)$

Then $V_{IF} = V_{RF} \cdot \text{Conductivity}$
$$= K \cdot V_{RF}\Big|_{\omega t = B}^{B+\pi} + 0 \cdot V_{RF}\Big|_{\omega t = B+\pi}^{B+2\pi}$$

$$\text{DC Component} = \int_{\omega t = B}^{B+\pi} AK\cos(\omega t)\,dt$$
$$= -AK\sin(\omega t)\Big|_{\omega t = B}^{B+\pi}$$
$$= AK[\sin(B) - \sin(B+\Pi)]$$
$$= AK[\sin(B) + \sin(B)]$$
$$= 2AK[\sin(B)]$$

Figure 7. Alternative to derivation of figure 6.

tion of the sinusoidal curve (near the zero-crossing points) where the output voltage varies almost linearly with input phase. This portion is used where a linear transfer characteristic is required.

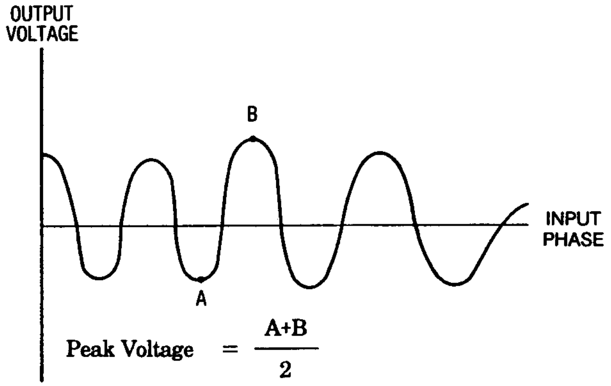
As can be seen from the derivation of Figure 7, peak voltage and sensitivity typically vary with rf power, but not with LO power. This is based on the assumption that the LO power is modulating the diode conductivity between two values, while the rf power is not affecting diode conductivity. In theory and in practice, this has been found to be true only when the rf power is much lower than the LO power (difference exceeds approximately 6 to 10 dB) and the LO power is sufficient to turn the diodes completely on with a duty cycle near 50%.

In cases where the peak voltage or sensitivity is insufficient, it is possible to use a video amplifier to increase the output voltage. However, the propagation delay of the amplifier will slow down the response of the rf discriminator. Minimizing propagation delay is important in phase-locked loops, which require immediate error correction.

In practice, diode and circuit imbalances cause the output to deviate from the expected value. For example, these imbalances will cause a dc offset voltage to appear at the IF port when the LO is applied, even without an rf signal present. Figure 8 shows a typical output-voltage versus input phase curve.

Discriminator

The key specifications of a frequency discriminator are similar to those of a phase detector (mentioned earlier), and may include linearity, slope over a given part of the curve, peak voltage, absolute output voltage at certain input frequencies, and maximum deviation from the ideal curve (typically sinusoidal or linear).



$$\text{Peak Voltage} = \frac{A+B}{2}$$

$$\text{DC Offset} = \frac{A-B}{2}$$

$$\text{Phase Error Ratio} = \frac{\text{Peak Voltage}}{\text{DC Voltage}} = \frac{A+B}{A-B}$$

Sensitivity = slope over a defined area (normally near zero crossing).

Figure 8. Typical phase detector output voltage versus input phase.

Many benefits are gained by specifying the frequency discriminator as a subassembly, rather than by separating the delay line and phase detector. The primary benefit is ease of alignment. When using a sealed, stand-alone phase detector, trying to adjust the delay length to the required accuracy (perhaps ± a few tens of picoseconds or better) may require trimming a coaxial delay line to within a few thousandths of an inch. A much better approach is available when the discriminator and delay line are integrated. It is then possible to simply coarse-tune the cable and provide fine tuning on the printed circuitry within the unsealed phase detector. In addition, it is possible to make slight adjustments, as required, to meet such specifications as sensitivity and slope. These adjustments could not be made to a sealed, stand-alone phase detector. Phase shifters may also be added to allow null spacing and null location to be adjusted independently.

While discriminators can provide a simple and inexpensive method of making instantaneous frequency measurements, a major disadvantage is that the discriminator's output voltage may become unpredictable when more than one signal is present at the input. The issue is a rather complex one and is discussed in detail in reference (7).

One important characteristic of discriminators with coaxial delay lines is that they are typically very sensitive to temperature, especially when taken below room temperature. This sensitivity problem can be diminished by improving the stability of the delay line, as discussed above.

X/Ku Band Discriminator

A WJ custom X and Ku-band discriminator and its corresponding block diagram are shown in Figures 9 and 10.

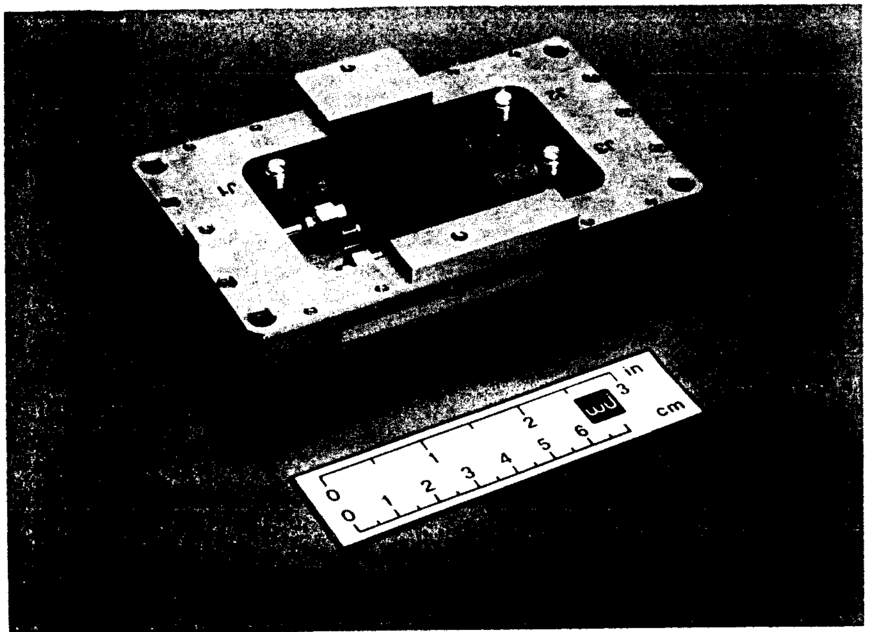


Figure 9. WJ X/Ku-band frequency discriminator.

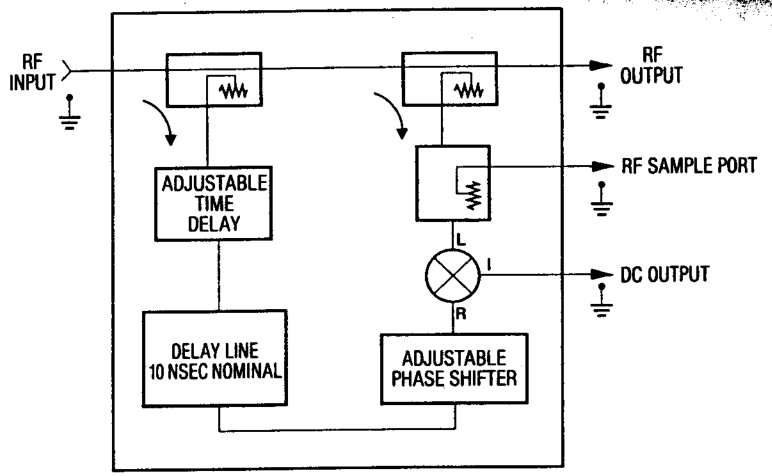


Figure 10. WJ X/Ku-band frequency discriminator.

The discriminator contains an integrated coaxial delay line, several directional couplers, a WJ mixer functioning as a phase detector, a selectable phase shifter, a coaxial delay line, and selectable microstrip line lengths to fine-tune the time delay. This discriminator has been designed to operate under full military environmental conditions.

Several unique performance requirements were considered during the design of this unit (see Table 1). The insertion loss of the through-path and the output peak voltage are both critical specifications. The couplers were carefully designed to avoid coupling away too much power and degrading insertion loss. At the same time, the couplers had to be designed to provide enough power to the phase detector to meet the peak voltage requirement. No dc power is applied to this unit.

In addition, accuracy of the output voltage null locations was a key specification that affected the design. To achieve the required accuracy, sections of micro-

Parameter	Typical Performance
Input power	+15 dBm min.
Output Voltage	200 mV peak
Through Path Insertion Loss	2.0-2.5 dB
Null accuracy, +20°C to +95°C	+/-10 MHz
Null accuracy, -55°C to +20°C	+10 / -50 MHz

Table 1. Key performance parameters of WJ X/Ku-band discriminator.

strip line were judiciously placed so that they could be selectively bonded into or out of the circuit, fine-tuning the electrical delay.

Since the absolute null location was specified (not just the null spacing), phase shifters were incorporated into the design to account for any dispersive phase shifts that might occur at discontinuities, such as bends in the delay line cable or transitions from microstrip to coax. By utilizing different bonding patterns, the phase shift can be adjusted to any value between 0° and 360° in 45° increments. All of these adjustments are done at WJ prior to sealing the MIC.

Automated Test

A key to the efficient manufacturing of the X/Ku band discriminator is automated testing, since the combination of broadband performance and closely spaced null locations make the number of measurement points immense. Over 100 nulls and over 100 peaks must be measured, along with over 200 sensitivity points. As these tests would take about a day if done manually, a custom automated test station has been developed which reduces the testing time to approximately 5 minutes. Since the tuning and alignment is interactive, this module could not be efficiently produced with a manual test station.

UHF-Band Discriminator

Figures 11 and 12 show a WJ UHF-band discriminator. Key performance characteristics are listed in Table 2. This discriminator contains mixers, TO-8 cascadable amplifiers, lumped-element power splitters, and a SAW delay line.

This discriminator produces two output voltages. The quadrature output has its voltage-versus-frequency curve shifted 90 degrees from the in-phase output. In addition, the mode-control switch allows a 180-degree phase inversion of both voltage-versus-frequency curves. By selecting the desired output and mode-control position, it is possible to obtain the required number of zero-crossings using a delay line 1/4 the normal length. This reduces the size of the overall discriminator. Alternatively, by using a weighted summing of the two outputs, it is possible to obtain any arbitrary shifting of the voltage-versus-frequency curve (without affecting the null spacing or the period of the sinusoidal output).

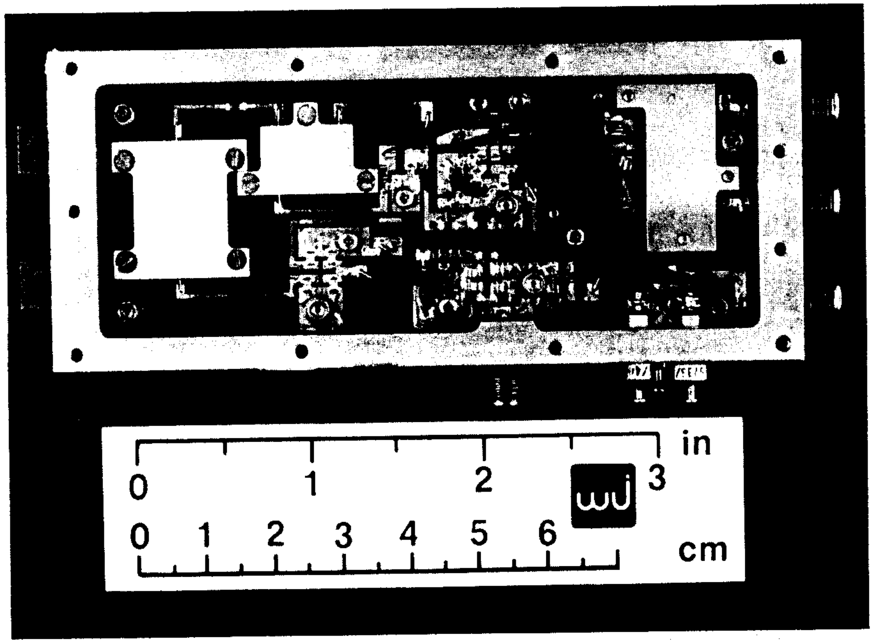


Figure 11. WJ UHF-band discriminator.

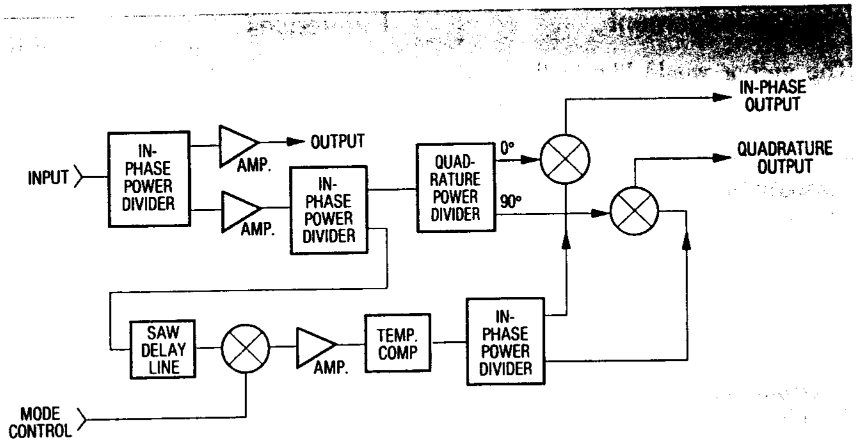


Figure 12. WJ UHF-band discriminator.

Conclusion

Discriminators play an important role in instantaneous frequency measurement, combining low cost and high accuracy at and above room temperature.

Areas where future technological advancement would broaden the applications for discriminators include improved delay-line stability over temperature (especially below room temperature) and an improved ability to detect and compensate for multiple simultaneous input signals.

Parameter	Typical Performance
Frequency (approx.)	500 MHz
Input power	0 ± 4 dBm
Peak Output Voltage	250 ± 50 mV
DC Offset	<10 mV

Table 2. Key performance parameters of WJ UHF-band discriminator.

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While in the Subsystems Division, Mr. Ferr was responsible for the design and development of an X/Ku-band discriminator and a prototype 3-band, high dynamic range, VHF-band through Ku-band receiver front end. Mr. Ferr also designed several MIC thin-film circuits, including directional couplers, microwave attenuators, rf amplifiers, and microstrip filters. He also developed several software tools, including a chain analysis program and a spur-search program.

Mr. Ferr holds a BSEE from California State Polytechnic University, Pomona, where he graduated Magna Cum Laude. He is a member of Eta Kappa Nu and the IEEE.