The Design of Ultra Narrow-Band Amplifiers for High Sensitivity Receiver Front-Ends Using Negative Resistance Devices for ESM, ECM, ECCM, ELINT, Radar, Satellite & Telecommunication Applications

BY

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TOPICS COVERED

- Review general block diagrams of various RF, Microwave & Millimeter Wave Receiver Front-Ends used in:
  - Defense & Radar Systems
  - Space Systems
  - Telecommunication
  - Test & Measurement (ATE) Equipment

- Review mathematical equations & parameters that define sensitivity, selectivity & noise in narrow band receiver front-ends.

- Review existing passive filter technology & techniques that achieve 1% to 0.01% narrow bandwidths and determine which ones are compatible for integration with PC's, IC's, MIC's & MMIC's.

- Propose a solution of applying reflection amplifier techniques that offer gain & filter bandwidths of 1% to 0.004% by just using a 3 section bandpass filter with 10% bandwidth.

- A patented design approach & technique is presented of a 25 dB reflection amplifier using 3 dB Quadrature Hybrid, matched 3 section bandpass filters, and matched negative resistance tunnel diodes that can achieve bandwidths of 1% to 0.004% by adjusting two resistors R_{SER} & R_{SH}.

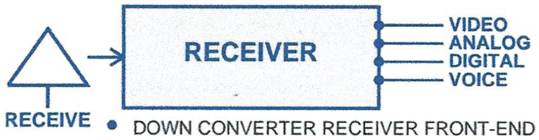
- Design of narrow band 25 dB gain amplifier and filter is offered that is compatible with PC's, MIC's, IC's, MMIC's and can be used in frequency ranges of 1 KHz to 100 GHz.

- A low cost solution is offered on how to design miniature, lightweight, narrow band amplifier front-ends using existing and simple filter designs and mature technologies and techniques that have existed since the 1960's.

TYPICAL RECEIVER BLOCK DIAGRAMS

FOR

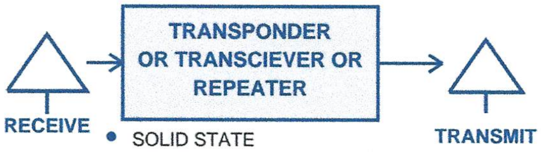
- Defense Platforms
- Radars
- Space Applications
- Telecommunications
- Test & Measurement Equipment and ATE



- DOWN CONVERTER RECEIVER FRONT-END
- UP-CONVERTER FRONT-END
- CHANNELIZED RECEIVER FRONT-END
- IFM RECEIVER FRONT-END
- TUNER/SUPERHETRODYNE FRONT-END

$$V_{(input)} = \underset{\substack{\downarrow \\ \text{AMPLITUDE}}}{A} \cos(\underset{\substack{\downarrow \\ \text{FREQUENCY}}}{\omega_c t} + \underset{\substack{\downarrow \\ \text{PHASE \&} \\ \text{MODULATION}}}{\phi_t})$$

MOST RECEIVERS ARE DESIGNED AND APPLIED TO SOLVE ABOVE EQUATION



- SOLID STATE
- SET-ON JAMMER (Pulse on Pulse)

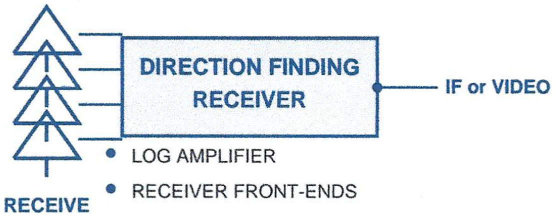
Minimum Detectable Signal (MDS):

$$MDS = -114 + NF + 10\log(B_r)$$

NF is in dB

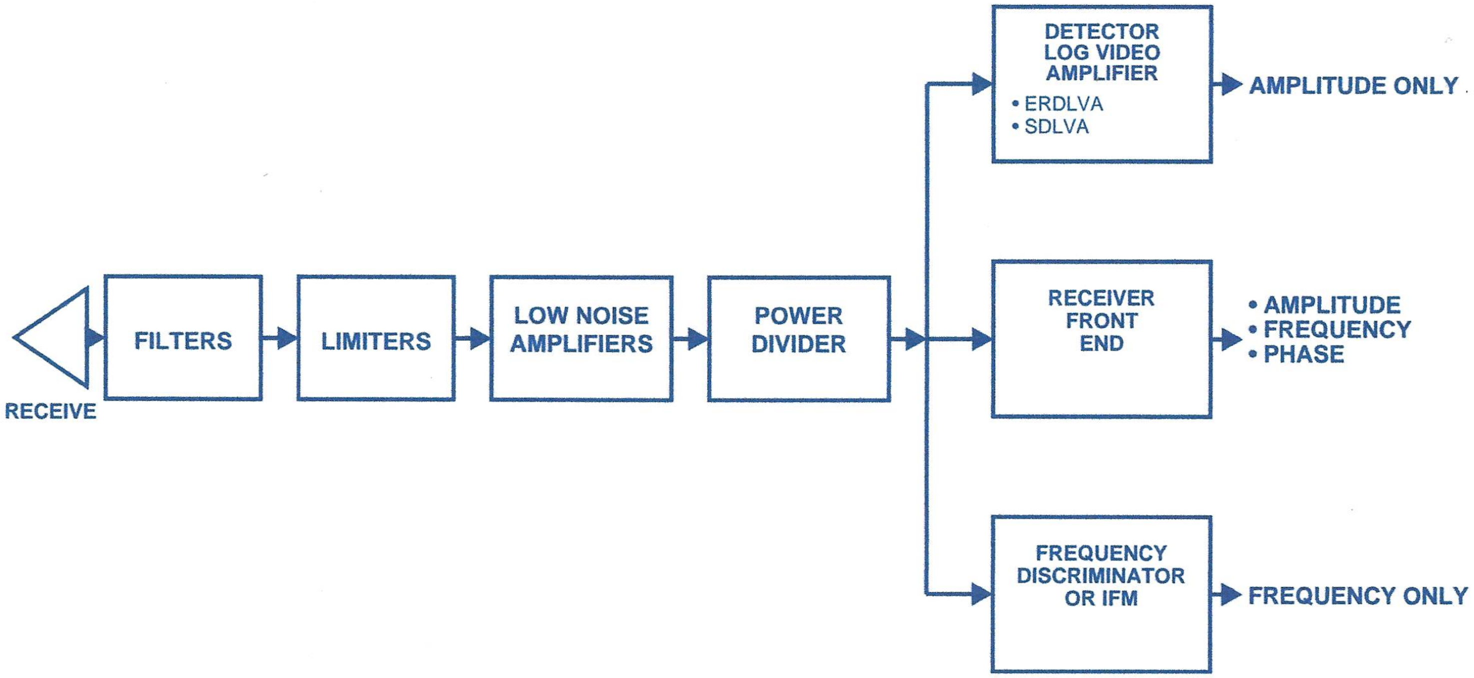
Br = RF channel bandwidth (MHz)

RECEIVER SENSITIVITY IS DIRECTLY PROPORTIONAL TO BANDWIDTH.



- LOG AMPLIFIER
- RECEIVER FRONT-ENDS

TYPICAL EW, ECM, ESM RECEIVER FRONT-END



RECEIVE

FILTERS

LIMITERS

LOW NOISE AMPLIFIERS

POWER DIVIDER

DETECTOR LOG VIDEO AMPLIFIER
- ERDLVA
- SDLVA

AMPLITUDE ONLY

RECEIVER FRONT END

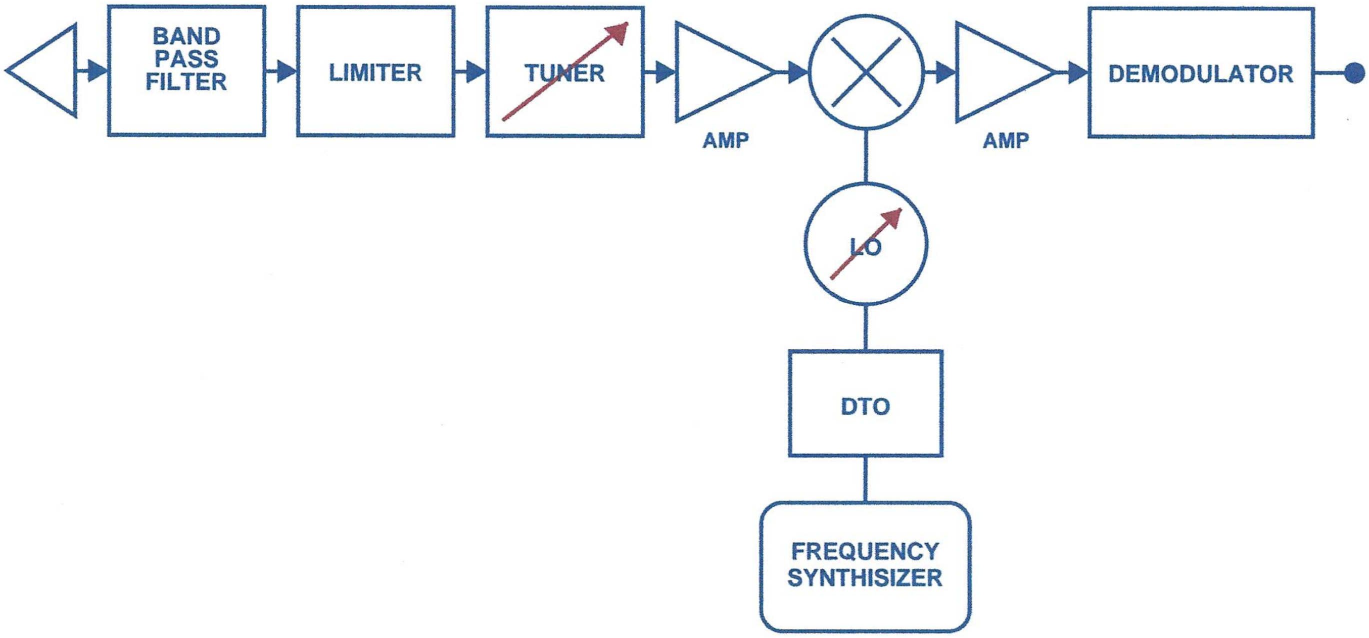
- AMPLITUDE
- FREQUENCY
- PHASE

FREQUENCY DISCRIMINATOR OR IFM

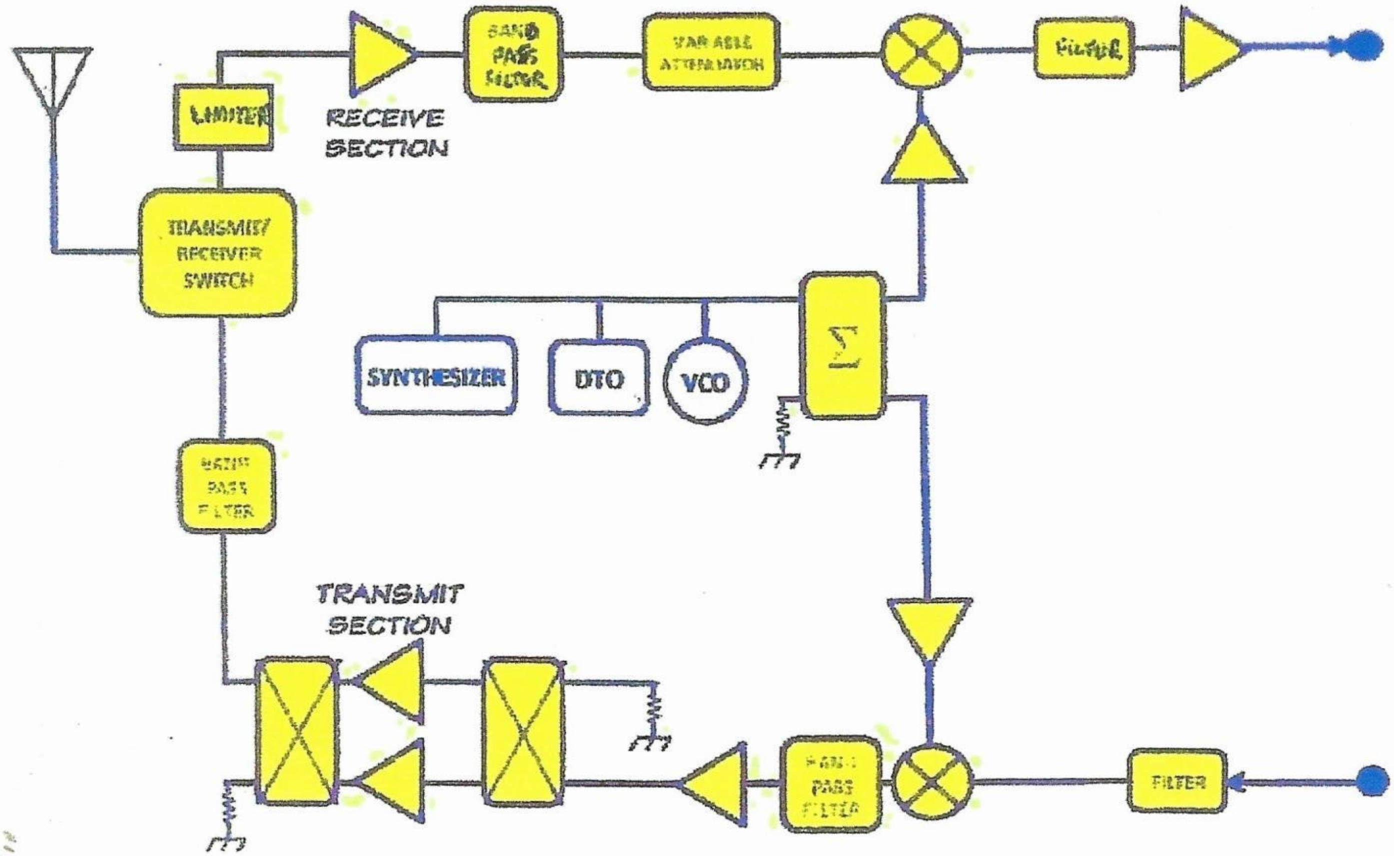
FREQUENCY ONLY

$$V_{(input)} = \underset{\substack{\downarrow \\ \text{AMPLITUDE}}}{A} \cos(\underset{\substack{\downarrow \\ \text{FREQUENCY}}}{\omega_c} t + \underset{\substack{\downarrow \\ \text{PHASE \& MODULATION}}}{\phi_t})$$

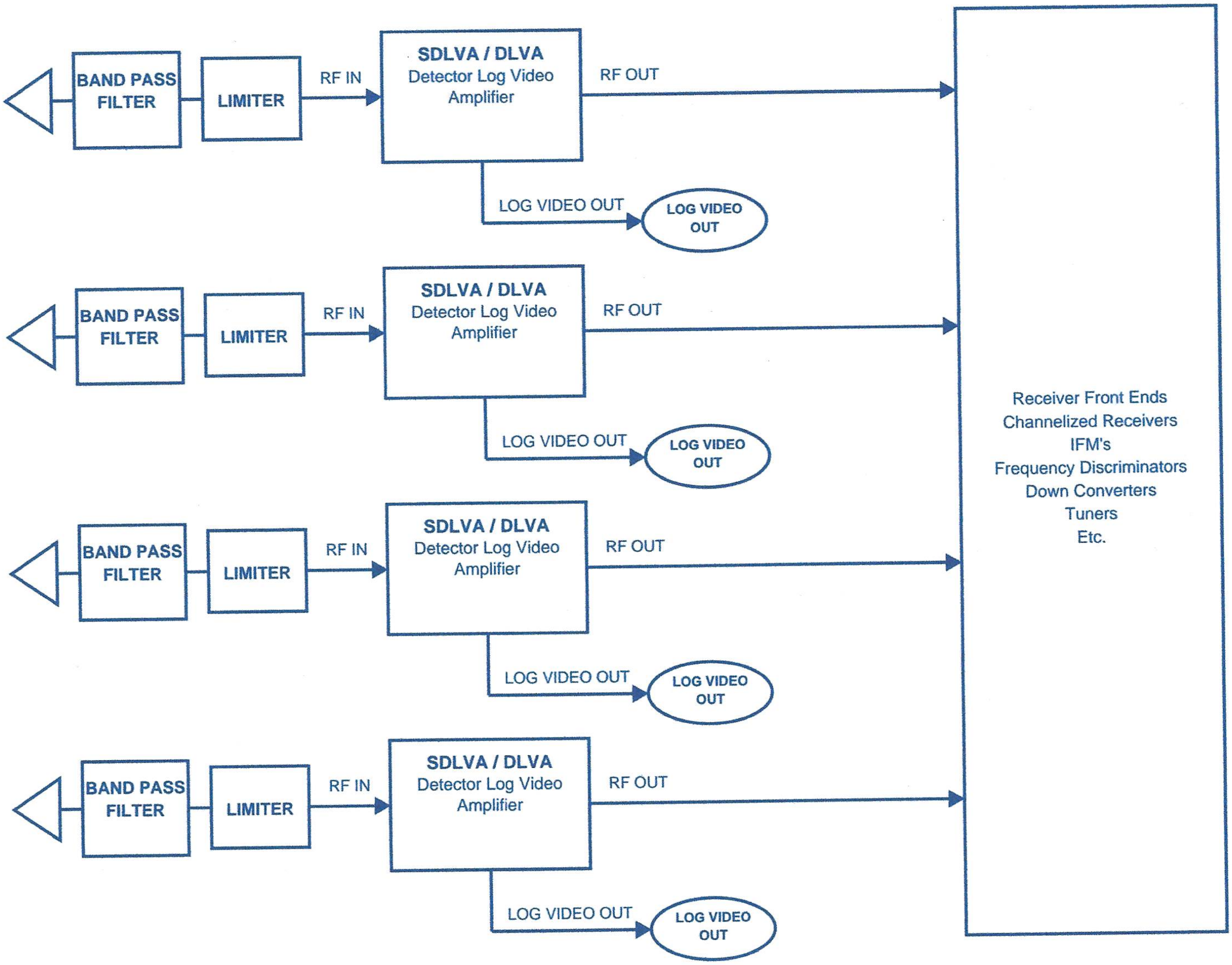
TUNER / SUPERHETRODYNE FRONT-END



TYPICAL TRANSCEIVER / TRANSPONDER BLOCK DIAGRAM

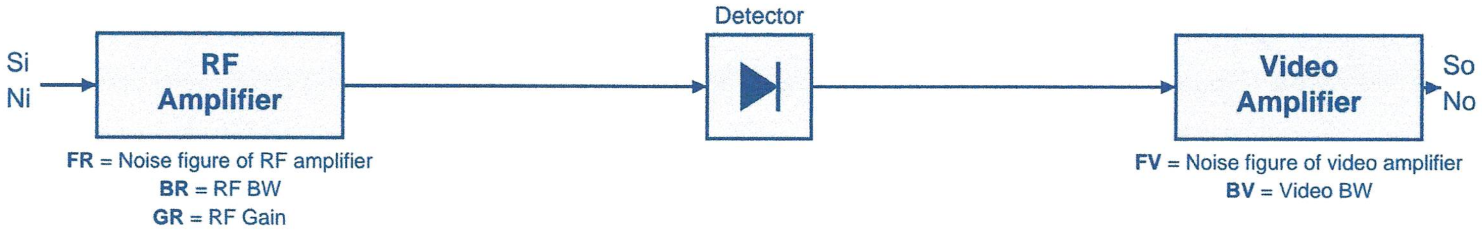


TYPICAL RADAR WARNING RECEIVER FRONT-END OR DIRECTION FINDING RECIEVER FRONT-END SUB-SYSTEM



TYPICAL RADAR WARNING OR DIRECTION FINDING RECEIVER FRONT-ENDS USE:-

- **DETECTOR LOG VIDEO AMPLIFIERS (DLVA's)**
- **SDLVA's**
- **DIODE DETECTOR CIRCUITS**



FR = Noise figure of RF amplifier
BR = RF BW
GR = RF Gain

FV = Noise figure of video amplifier
BV = Video BW

Amplified Diode Video Receiver

RECEIVER SENSITIVITY IS DETERMINED BY TSS AND BANDWIDTH

$$\mathbf{TSS} = -114 + F_R + 10\,\mathrm{Log}\left[\,6.31\,B_V + 2.5\sqrt{(2B_R B_V - B_V^2)} + \frac{AB_V}{(G_R F_R)^2}\right]$$

$$\mathbf{TSS} = -110 + F_R + 10\,\mathrm{Log}\sqrt{(2B_R B_V - B_V^2)}$$

FOR $B_R >> B_V$

$$\mathbf{A} = \frac{4F_V R_V}{KTK_{SL}^2} \times 10^{-6}$$

and

RV = detector video resistance
T = temperature in degrees Kelvin
KSL = detectors square law K in mV/mW
FV = video amplifier noise factor
K = Boltzmann's constant (1.38 × 10^{-23} J/°K)
GR = GAIN OF LOW NOISE AMPLIFIER
FR = NOISE FIGURE OF AMPLIFIER

KEY TO INCREASING SENSITIVITY AND SELECTIVITY OF RF / MICROWAVE / MM WAVE RECEIVER SYSTEMS

- Reducing Bandwidth & Noise
- Increasing "Q" of Circuits

PRESENT TECHNIQUES

Filter Type	Frequency Range	Typical Q	Min % Bandwidth	IC/MMIC Compatible
RC passive	1 kHz – 1 MHz	Very low	> 20%	Good IC, poor selectivity
Lumped LC	100 kHz – 1 GHz	20 – 300	0.3% – 10%	Limited on-chip Q
Quartz crystal	1 kHz – 200 MHz	5,000 – 100,000+	0.001% – 0.1%	No
Ceramic / dielectric resonator	100 kHz – 40 GHz	200 – 15,000	0.05% – 3%	No
SAW (Surface Acoustic Wave)	30 MHz – 3 GHz	500 – 5,000	0.03% – 2%	Not monolithic
BAW / FBAR (Bulk Acoustic Wave / Film Bulk Acoustic Resonator)	700 MHz – 8 GHz	800 – 3,000	0.1% – 3%	Not monolithic
Planar microstrip / stripline	500 MHz – 100 GHz	30 – 500	1% – 20%	Yes; MMIC compatible
Coaxial / cavity / waveguide	10 MHz – 100 GHz	500 – 50,000	0.02% – 2%	No
Superconducting	100 MHz – 100 GHz	10,000 – 1,000,000+	< 0.01% possible	Special only
YIG (Yttrium Iron Garnet)	500 MHz – 50 GHz	500 – 10,000	0.05% – 1%	No — Magnetic

PROPOSED TECHNIQUES

- **Negative Resistance – R:** Tunnel Diodes, 3 Section Bandpass Filters and Quadrature Coupler
- **Negative Resistance – R:** Tunnel Diodes, 3 Section Bandpass Filters and Circulator

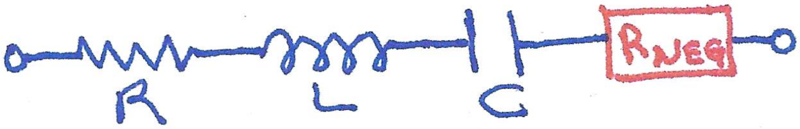
FILTER DESIGN USING SERIES & SHUNT RESONATORS

Q, BANDWIDTH & NOISE CONTROL

for Receiver Sensitivity with Negative Resistance

OVERVIEW

Filters are composed of resonant sections arranged in series and shunt forms. Their performance depends on Q, bandwidth, and loss. Controlling Q improves selectivity, reduces noise, and minimizes number of sections.



SERIES RESONANT SECTION

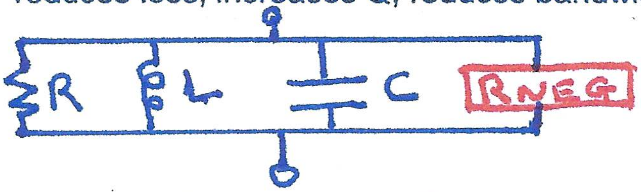
Series RLC circuits determine passband behavior. Loss is represented by series resistance R.

$$Q = \omega L/R = 1/\omega CR = \frac{\text{Reactive Power}}{\text{Resistive Power}} = f/B \quad (B = \text{Bandwidth},\ \omega = 2\pi f)$$

$$\text{Bandwidth} = R/(2\pi L) \qquad \omega_L = 1/\omega C \qquad \omega_0 = 1/\sqrt{LC}$$

Adding negative resistance: $R_{eff} = R - |R\mathbf{NEG}|$ → reduces loss, increases Q, reduces bandwidth

For stability: $R > R_{NEG}$



SHUNT (PARALLEL) RESONANT SECTION

Parallel RLC circuits determine selectivity. Loss is represented by shunt resistance Rp.

$$Q = \omega_0 R_p C = R_p / (\omega_0 L) = \frac{\text{Reactive Power}}{\text{Resistive Power}} = f/B \quad (B = \text{Bandwidth},\ \omega = 2\pi f)$$

$$\text{Bandwidth} = 1/(2\pi R_p C) \qquad \omega_0 C = 1/\omega_0 L \qquad \omega_0 = 1/\sqrt{LC}$$

Adding negative resistance in parallel increases effective Rp by cancelling loss.

$R_{eff} = R_p \ || \ (-R_{NEG})$ → Effective resistance increases → Q increases → Bandwidth decreases

For stability: $R_{NEG} > R \qquad R_{NEG} = \dfrac{Rp \cdot RNEG}{(RNEG - Rp)}$

RECEIVER SENSITIVITY, NOISE, BANDWIDTH AND Q RELATIONSHIP

$$\text{Sensitivity} = -174 + 10\log_{10}(B) + NF + SNR$$

Where:

–174 dBm/Hz = thermal noise floor at 290 K
B = bandwidth (Hz)
NF = noise figure (dB)
SNR = minimum signal-to-noise ratio (dB)

Speed of Light:

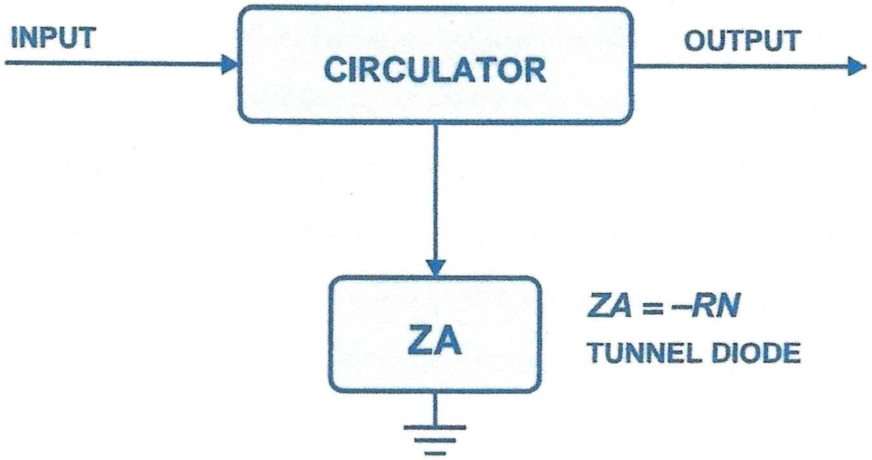
$\mathbf{f = c/\lambda} \qquad c = 3 \times 10^8$ m/s = 186,000 miles/s
For $f = 1$ Hz, $\lambda = 186{,}000$ miles

Thermal Noise:

$N = kTB$ (Watts) $\qquad N \propto B \qquad k = 1.38 \times 10^{-23}$ J/K (Boltzmann Constant)
$V_N = \sqrt{(4kTBR)}$ Noise Voltage in Resistor
T = Absolute Temperature in Kelvin (290 K at room temperature)

Basic Negative Resistance (–R) Circuit Techniques Using Tunnel Diodes

Also Called Reflection Amplifier



INPUT

CIRCULATOR

OUTPUT

ZA

ZA = –RN

TUNNEL DIODE

$$\Gamma A = \frac{-RN - Z0}{-RN + Z0}$$

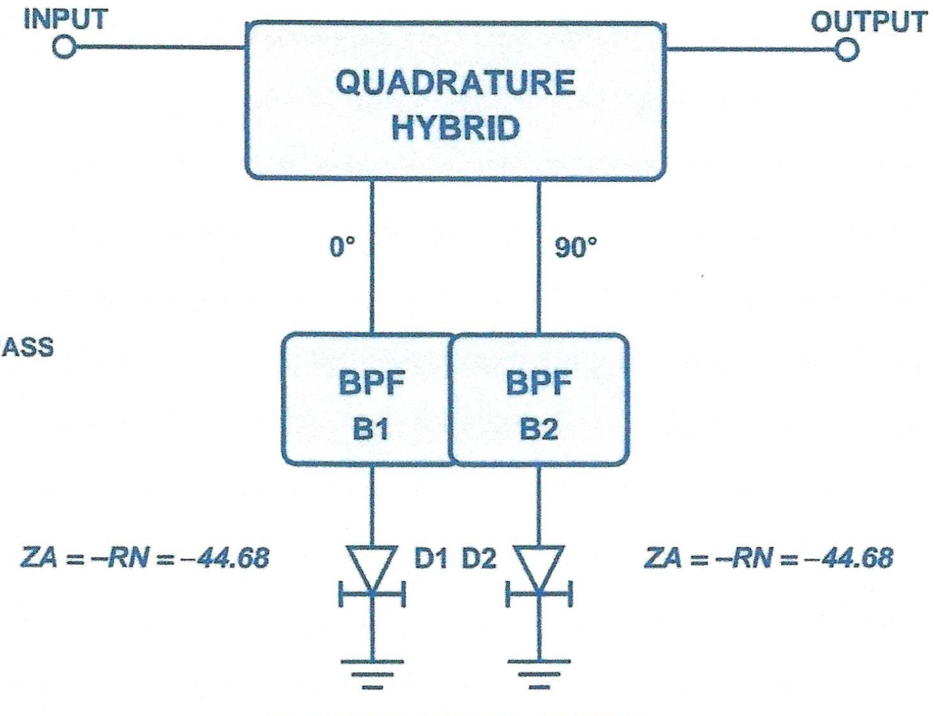
$$G \geq \left(\frac{RN + Z0}{RN - Z0} \right)^{2}$$

$$|\Gamma A| > 1$$

$$G = |\Gamma A|^{2}$$

–RN = 44.68 Ω

G = 25 dB Gain



INPUT

OUTPUT

QUADRATURE HYBRID

0°

90°

BPF B1

BPF B2

ZA = –RN = –44.68

D1 D2

ZA = –RN = –44.68

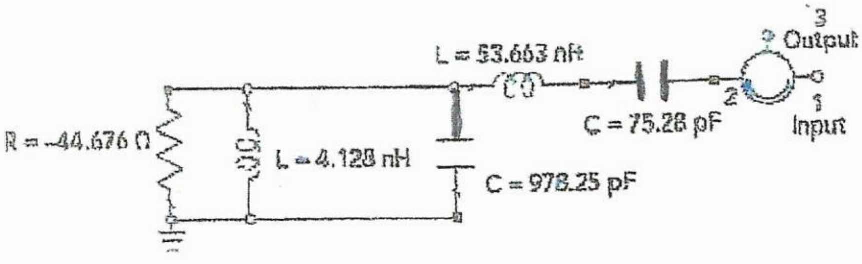
MATCHED
BPF – BAND PASS
FILTERS
B1 = B2 = B
D1 = D2 = D

MATCHED TUNNEL DIODES

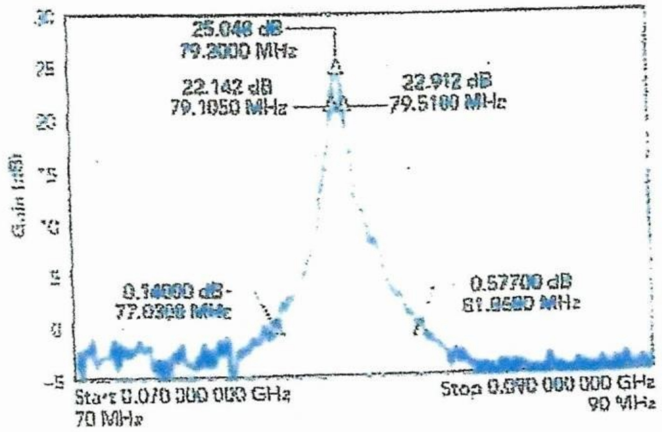
Assuming matched lossless circuit, matched band pass filters and tunnel diodes with –R = 44.68 Ohms, gain will be 25 dB.

Unique Circuit Using Circulator, 2-Section Bandpass Filter at 79.2 MHz and Tunnel Diode (Grayzel Negative Resistance Amplifier, GNRA)**

- Test results demonstrated 0.5% bandwidth was achieved at 79.2 MHz using Tunnel Diode with –R = 44.876 Ohms for a two section bandpass filter with bandwidth of 8.5% and gain of 25 dB.



GNRA with Two-section filter resonant at 79.2 MHz.



0.41 MHz 0.5%

GNRA measured results.

** **References:**

1. "A Negative Resistance Amplifier with 0.5 Percent Bandwidth," Microwave Journal, Vol. 66 No. 5, May 2023, pp. 90–94.
2. A. I. Grayzel, "Very Narrowband and Wideband Negative Resistance Amplifiers with a Tunable Center Frequency," U.S. Patent: US 11 863 131 B1, January 2, 2024.

Devices and Circuits Providing Negative Resistance (–R)

Devices

Gunn Diodes (J.B. Gunn, 1962, IBM)

- Mostly used for oscillators
- Can be used in reflection amplifiers
- Stability issues & biasing considerations
- Heat sinking required

IMPATT Diodes (Impact Ionization Avalanche Transit Time)

- Mostly used for oscillators
- Require high voltages
- Can be used in reflection amplifiers
- Stability & biasing challenges
- Heat sinking required

TRAPATT Diodes (Trapped Plasma Avalanche Triggered Transit)

- Mostly used for oscillators
- Require high voltages
- Can be used in reflection amplifiers
- Stability issues & biasing
- Heat sinking required

Tunnel Diodes (Leo Esaki, 1957; Nobel Prize 1973)

- Negative resistance region can be biased for –R operation
- Compatible with MMICs, ICs, microstrip & integrated circuits
- Small size & lightweight
- Used in space & radiation environments
- Biasing is tricky but practical
- Low noise performance
- Low power performance

Devices and Circuits Providing Negative Resistance (–R)

Circuits

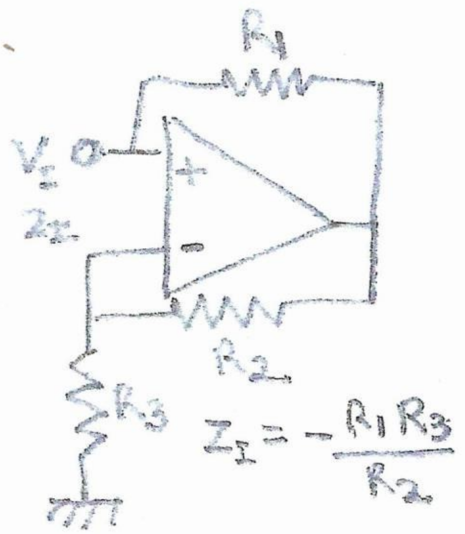
1.0 Operational Amplifiers (Op-Amps)

2.0 Linvill Circuits (J.G. Linvill, 1953, Bell Labs)

--- Used for generating –R, –L, –C, and –Z (impedance)

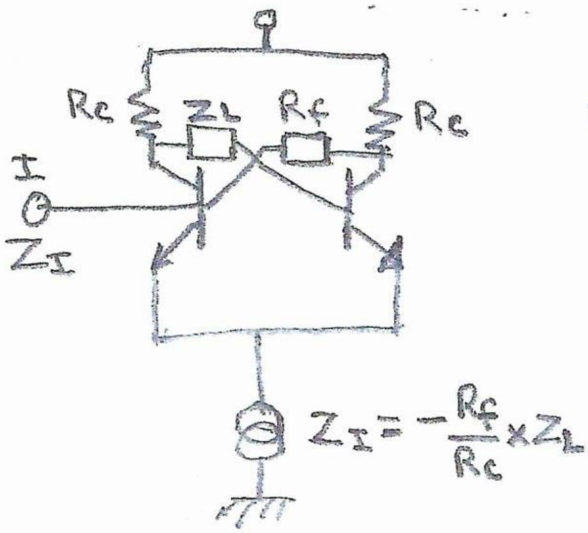
3.0 Cross Coupled Pairs

- --- BJT (Bipolar Junction Transistors – silicon)
- --- HBT (Heterojunction Bipolar Transistors)
- --- FET (Field Effect Transistors)
  - --- CMOS / NMOS (Complementary MOS)
  - --- MESFET (Metal Semiconductor FET)
  - --- pHEMT (Pseudomorphic HEMT)
  - --- InP HEMT / mHEMT (Metamorphic HEMT)
  - --- HEMT (High Electron Mobility Transistor)



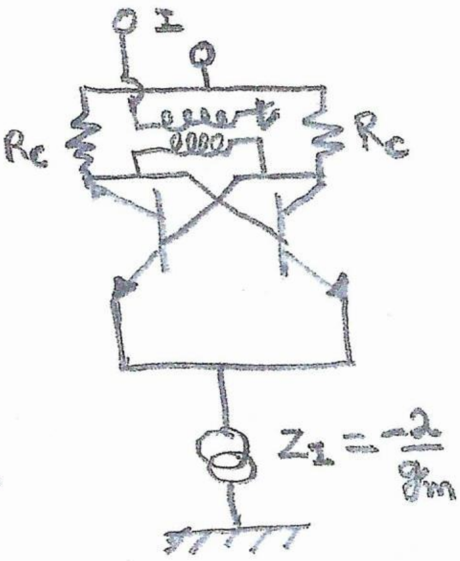
$Z_I = -\frac{R_1 R_3}{R_2}$

OP-AMP CIRCUIT



$Z_I = -\frac{R_f}{R_c} \times Z_L$

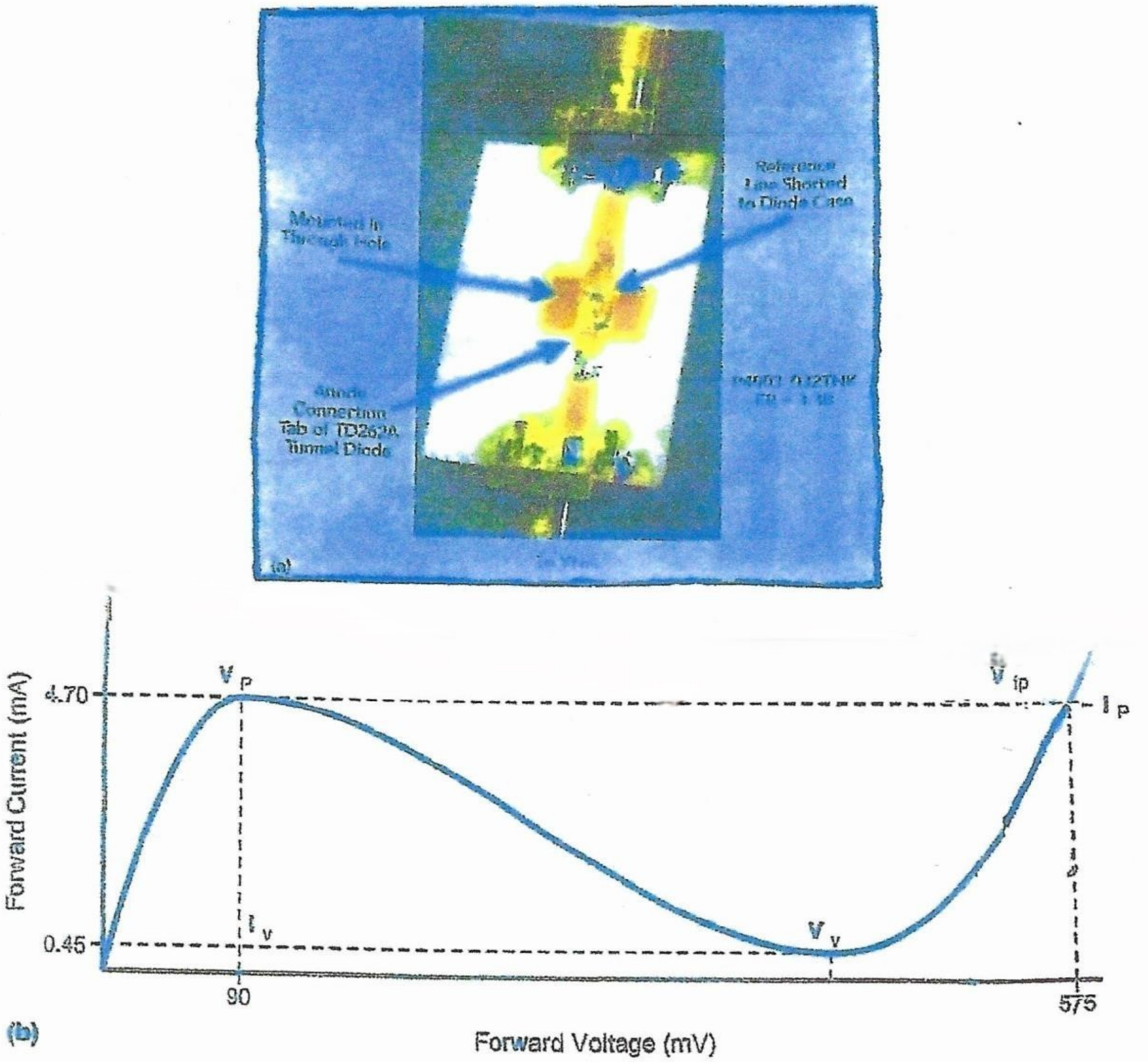
LINVILL CIRCUIT



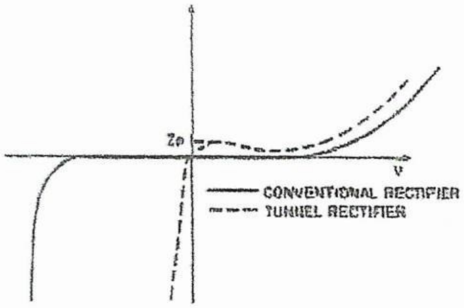
$Z_I = \frac{-2}{g_m}$

CROSS COUPLED PAIR

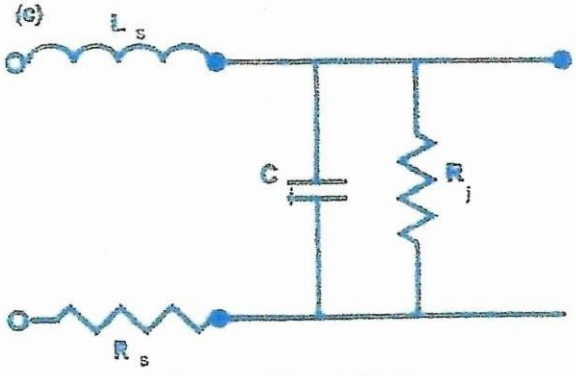
TD262A Tunnel Diode – Test Fixture, Characteristic Curve & Equivalent Circuit



TD262A tunnel diode test fixture (a) and characteristic curve (b).

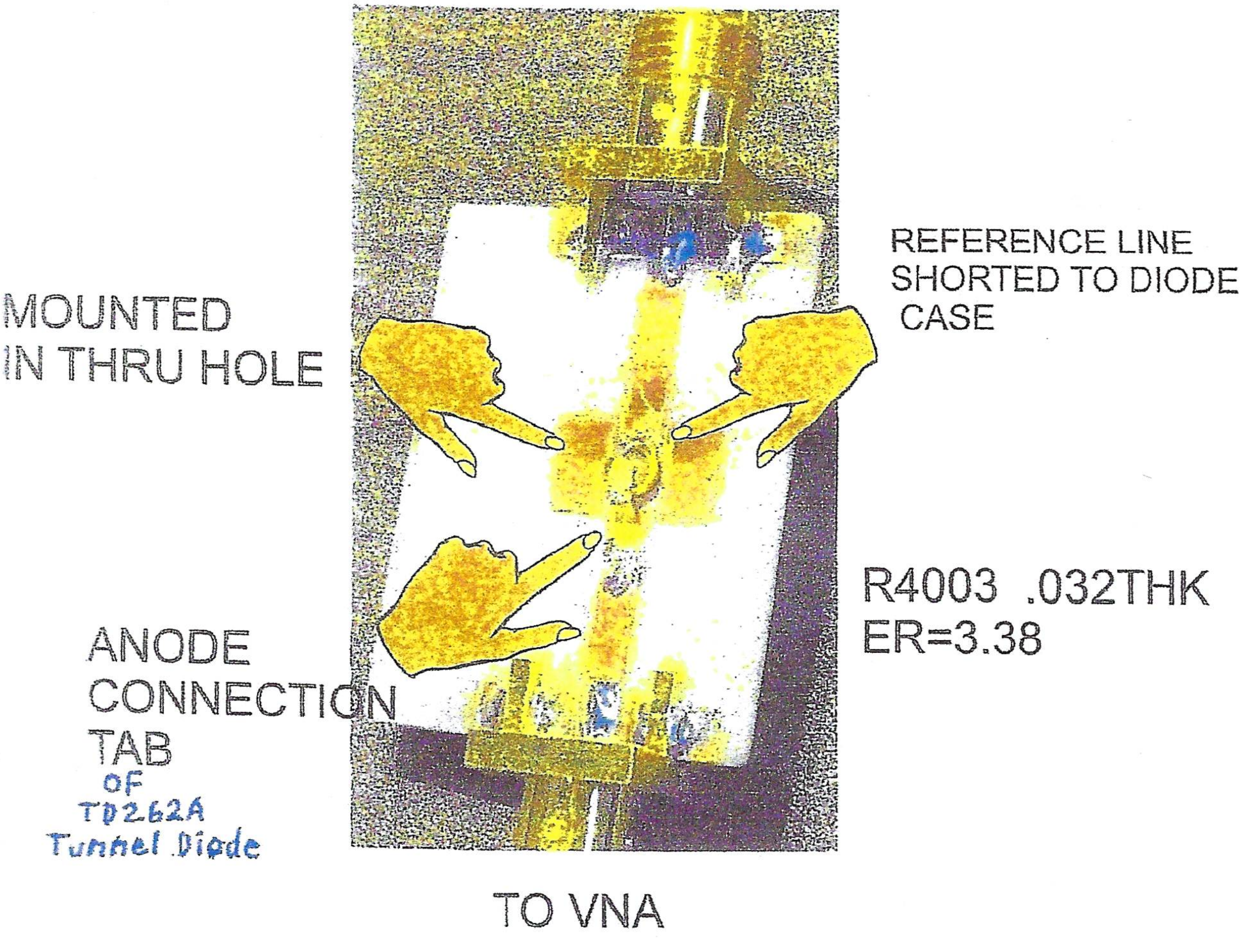


Characteristics curves for tunnel rectifier and conventional rectifier.

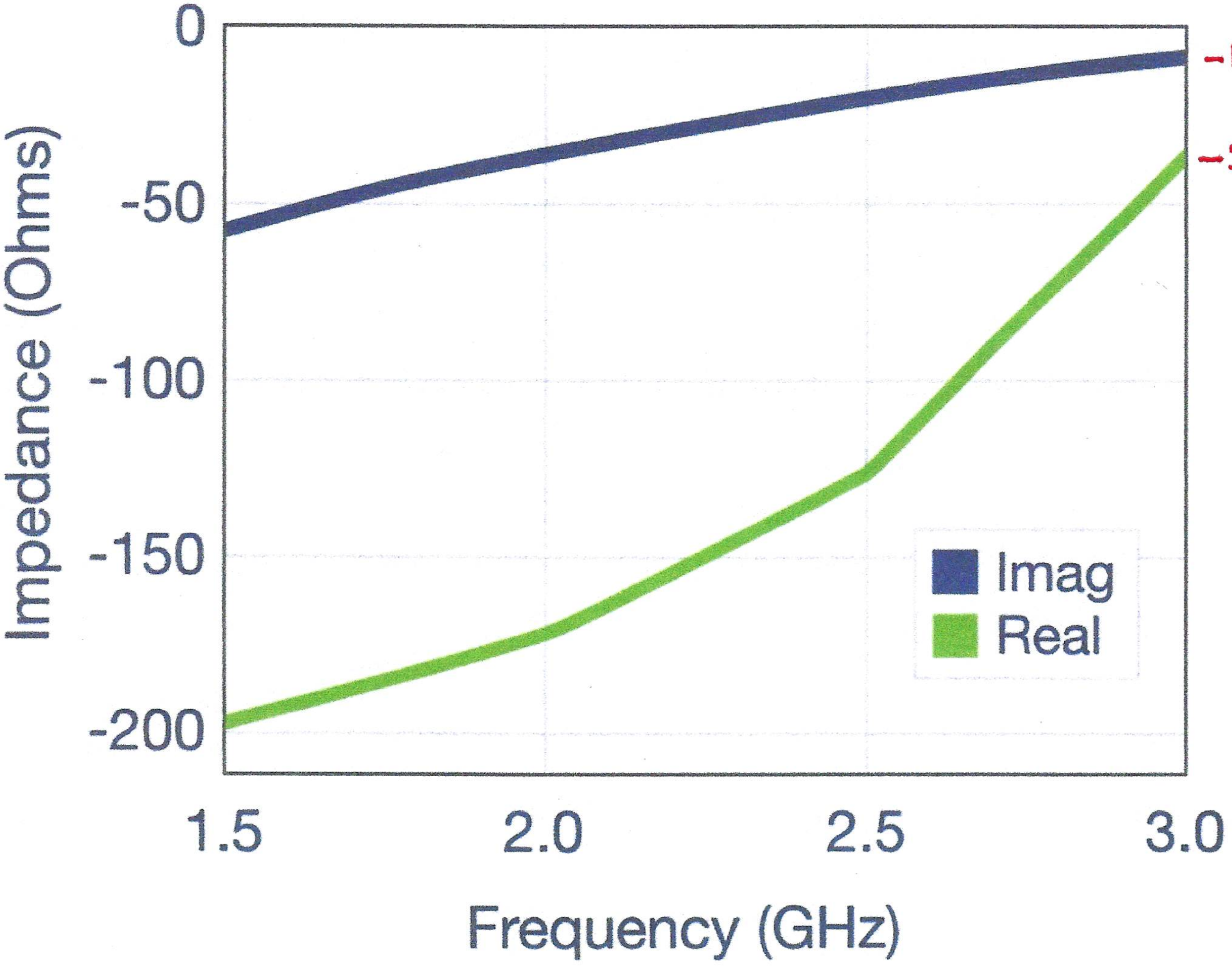


Packaged Tunnel Diode Equivalent Circuit

Fig. 2A Tunnel Diode Test Fixture



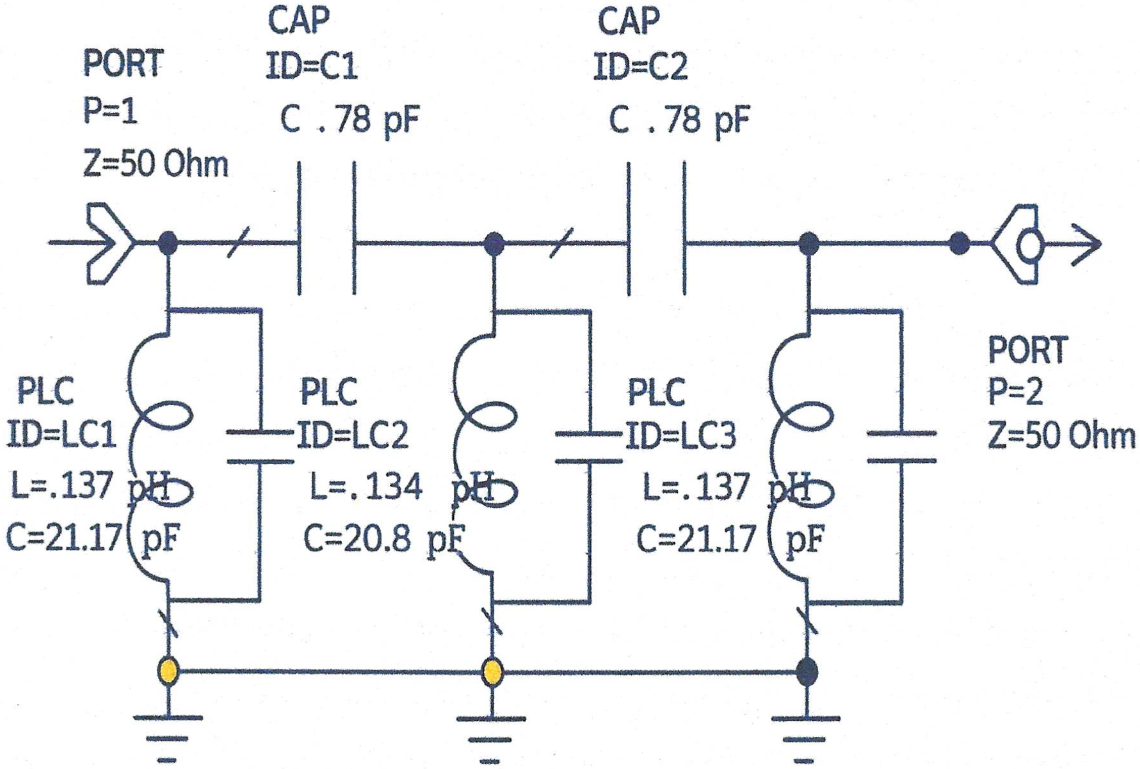
TD262A Tunnel Diode Measured Impedance

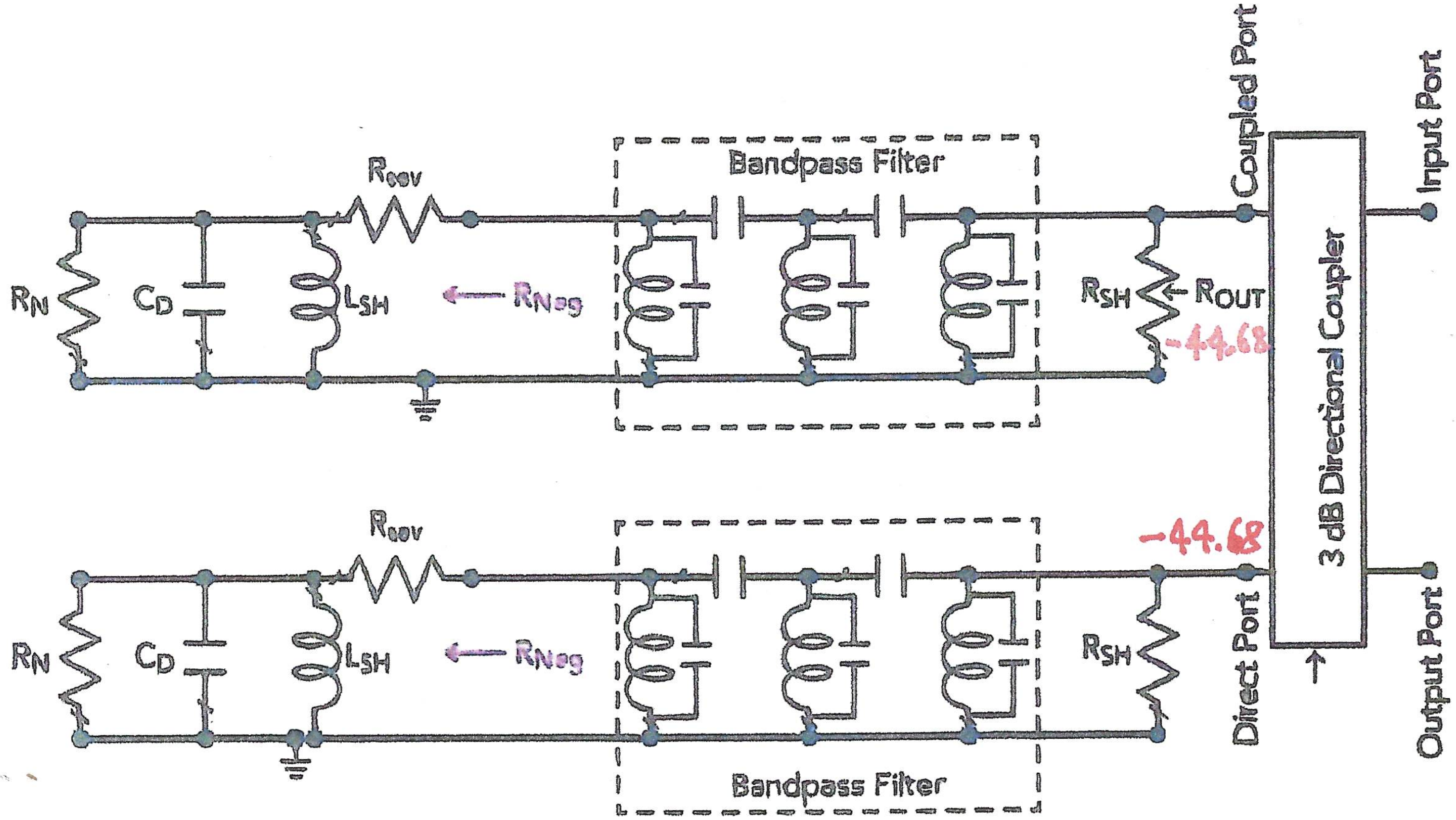


-12.7 Ω

-56.5 Ω

2.9 GHz, 3 Section Butterworth Bandpass Filter with 10% Bandwidth

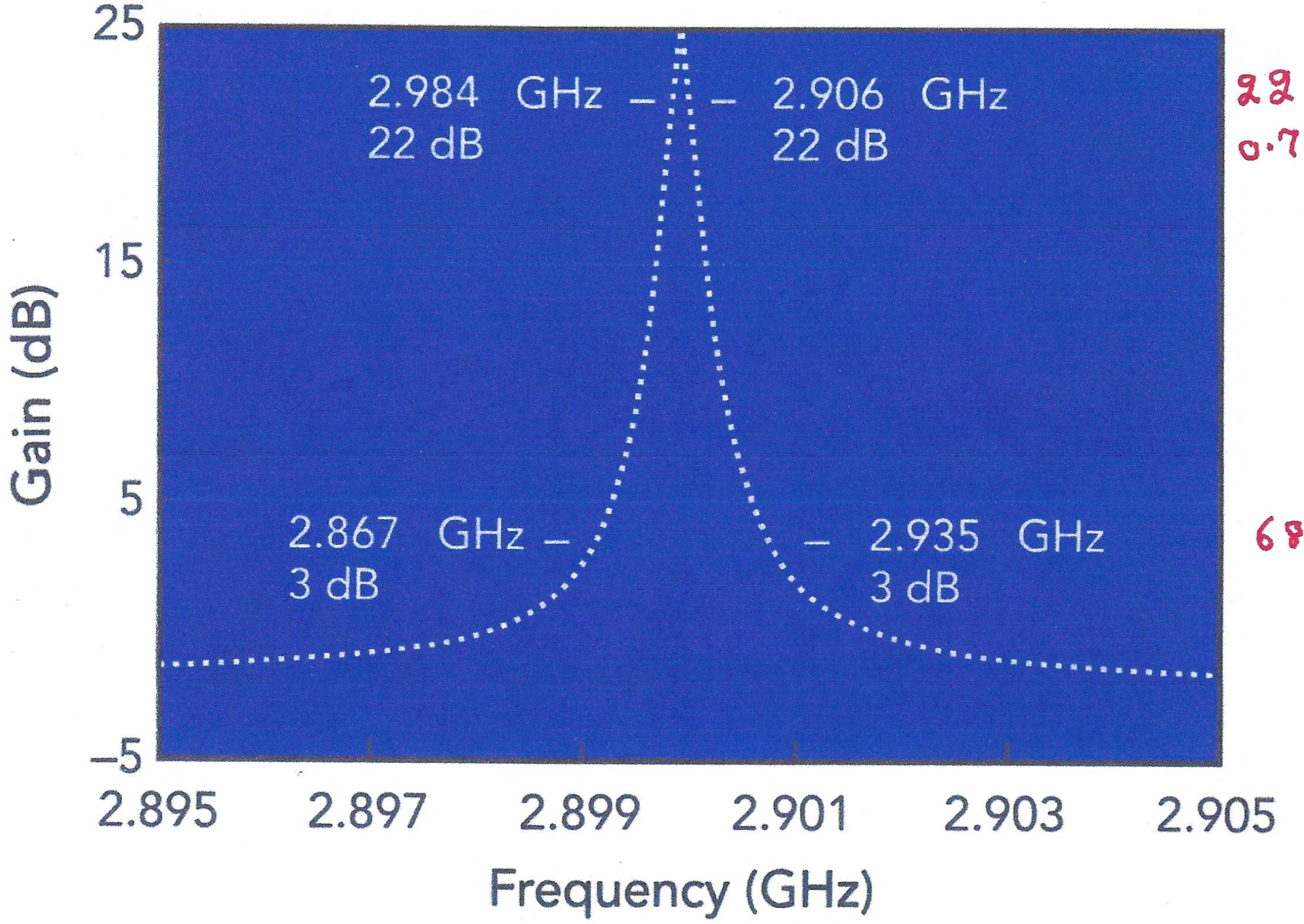




10%
BUTTERWORTH

Tunnel diode negative resistance amplifier schematic.

A. I. Grayzel and A. Gorwara, "Very Narrowband and Wideband Negative Resistance Amplifiers with a Tuneable Center Frequency Using a Coupler," *U.S. Patent 12 052 002 B2*, July 30, 2024.



22 MHz
0.76%

68 MHz

Gain versus frequency of negative resistance amplifier with R_{sh} = 100 Ω.

TABLE 1

RNEG, RSER, 3 DB BW, PERCENT BW AND DELTA AS A FUNCTION OF RSH

R_{sh} (Ω)	$R_{\text{ncă}}$ (Ω)	R_{ser} (Ω)	3 dB BW (MHz)	BW (%)	Delta (MHz)
100	-30.88	25.6	22	0.76	34
50	-23.6	32.9	5	0.17	25
25	-16	40.4	1.7	0.06	7
10	-8.2	48.3	0.190	0.034	3
5	-4.5	52.0	0.110	0.004	0.860

Device & Circuit Selection for Negative Resistance (–R) in Filters

Four Devices & Their Frequency Range

Device	Frequency Range	How –R is Generated	Noise Added
TUNNEL DIODE	DC to ~100 GHz (RTD — Resonant Tunnel Diode reported)	Quantum tunnelling at near-zero bias produces –R directly. No transistor circuit needed. Conventional Esaki: DC–4 GHz. RTD (Resonant Tunnel Diode): extends –R to mm-wave.	Flicker: negligible — ideal for DC & low freq. Shot: reduced in –R region. Thermal: reduced in –R region.
BJT CROSS-COUPLED PAIR	DC to ~2 GHz (Si)	Two BJTs — each collector drives the opposite base. Positive feedback regenerates energy → –R. Requires significant DC bias current.	Flicker: high (corner ~100 MHz, Si). Shot: dominant, unavoidable. Thermal: from base resistance r_b.
HBT CROSS-COUPLED PAIR	DC to ~40 GHz (SiGe) DC to ~80 GHz (InP)	Same collector-to-opposite-base topology as BJT. Heterojunction raises fT and reduces base current, lowering noise vs. BJT.	Flicker: present (corner ~1–10 MHz). Shot: present, reduced vs. BJT. Thermal: from base resistance r_b; lower than BJT.
FET CROSS-COUPLED PAIR (GaAs/InP HEMT)	DC to ~40 GHz (GaAs) DC to ~94 GHz+ (InP reported)	Each drain drives the opposite gate — positive feedback → –R. Current flows through a channel. No junction barrier is crossed.	Flicker: low (corner ~1–10 MHz). Shot: ABSENT — no junction. Thermal: channel noise only (dominant above 1 GHz).

Three Basic Noise Types

Noise Type	Origin	Which Devices — What Is Reported
Flicker (1/f)	Surface traps & defect states	Tunnel Diode: negligible — primary reason chosen for DC & low-frequency use. BJT: highest of all — corner up to ~100 MHz (Si). HBT: present, corner ~1–10 MHz — lower than BJT. FET: lowest — corner ~1–10 MHz; best transistor for low-frequency noise.
Shot	Current crossing a junction barrier	Tunnel Diode: reduced in –R region — negative dynamic conductance lowers noise current below forward-bias levels. BJT: dominant and unavoidable at all frequencies. HBT: present but reduced versus BJT. FET: ABSENT — current flows in channel; no junction barrier is crossed.
Thermal (Johnson)	Resistive elements & FET channel	Tunnel Diode: reduced in –R region — effective noise resistance decreases in negative conductance. BJT / HBT: from base resistance r_b (ohmic base region) — significant contributor. FET: channel thermal noise dominant above ~1 GHz — well characterised and predictable.

Data based on published research and reported industry achievements. 1 kHz to 100 GHz coverage. Device choice directly determines noise added to the signal path.

Benefits of Using Negative Resistance (Esaki & RTD Resonant Tunnel Diodes) in Filters

- Narrower effective bandwidth → higher selectivity
- Lower noise floor → improved receiver sensitivity
- Potential replacement or enhancement to:
    - SAW / BAW filters
    - High-Q cavity filters
    - DSP-based filtering stages
    - Multi-section filters
- Longer detection range (radar / EW)
- Better signal-to-noise in congested spectrum
- Reduced power consumption
- Smaller / lighter hardware (vs. cavity filters)
- 3 to 10 times improvement in selectivity
- Eliminates need for high-Q passive filters
- Scalable from MHz to mmWave
- Compatible for integration with MMICs
- Tunable architectures possible

CONCLUSIONS

- A unique circuit has shown that a 25 dB low noise reflective amplifier is achieved by matched –56.5 ohm tunnel diodes and 3 dB quadrature hybrid at 2.9 GHz.

- This circuit has a bandpass (BPF) 3 section filter at 2.9 GHz with bandwidth of 0.004% with R_{SH} of 5 ohms shunt resistor across input terminals of filter, and 0.76% with R_{SH} of 100 ohms.

- There is no need for multi-section filters to achieve ultra narrow band filters. Just 3 sections are sufficient.

- By varying series R_{SER} resistor and controlling R_{SH} across input with tunnel diode termination, high Q performance can be achieved in simple 3 section filters for various % bandwidths at 2.9 GHz.

- Theoretically using tunnel diode for negative resistance and similar BPF filters & quadrature couplers in octave or multi-octave bands can be applied at other frequencies in the 1 kHz–100 GHz spectrum to achieve 1% to 0.004% bandwidths.

- These circuits can be very small and lightweight and suitable for integration with ICs, MICs, and MMIC circuits.

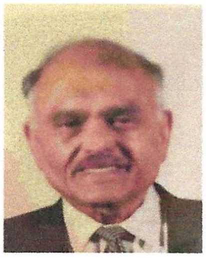
BIO-DATA OF AUTHORS

Dr. Alfred I. Grayzel — Ph.D., M.I.T.


Dr. Alfred Grayzel

Alfred I. Grayzel (M'55 · SM'85 · LM'92) was born in Brooklyn, N.Y. on May 24, 1933. He received a B.A. from Columbia College in N.Y.C. in 1954 and a B.S.E.E. from the Columbia School of Engineering in 1955. He received an M.S.E.E. and a Ph.D. in Electrical Engineering from M.I.T. in 1961 and 1963. He spent 17 years of his career at M.I.T.'s Lincoln Laboratory as a staff member. In 1975 he founded A.I. Grayzel Inc., which manufactured unconditionally stable varactor frequency multipliers and up-converters. The company was acquired by the Anzac Corporation in 1985. He is currently a consultant to Gorwara & Associates International Inc. (GAI), USA.

Dr. Ashok (Ash) Gorwara — Ph.D./D.S.E.E., University of London


Dr. Ashok (Ash) Gorwara

Dr. Ashok (Ash) Gorwara attended the University of London for B.S.E.E., M.S.E.E., and Ph.D./D.S.E.E. doctoral studies. Post-doctoral, he served as Lecturer at MIT and Northeastern University, Boston, USA, going on to further Research & Development at MIT-Lincoln Laboratories and Stanford Research Institute (SRI), California, for Electronic Warfare, Radar, ESM, ECCM, Surveillance, ELINT, Components, and Subsystems plus Satellite Communications. He was Founder, Owner, President, CEO and Chief Technical Officer of Planar Monolithics Industries Inc. (1989–2021). He is Presently President & CEO, CTO of Gorwara & Associates International Inc. Limited.

From 1976 to 1980 was Founder, President, CEO & CTO of Planar Microwave International Corporation, Sunnyvale, California. Acquired by Raytheon Company as its PLAMIC Division.

From 1980 to 1987 was Managing Director of Public Limited Company VITROC Elektroniks Limited, Solan, H.P., India, with Joint Collaboration with Danish, German Company, VITROHM.