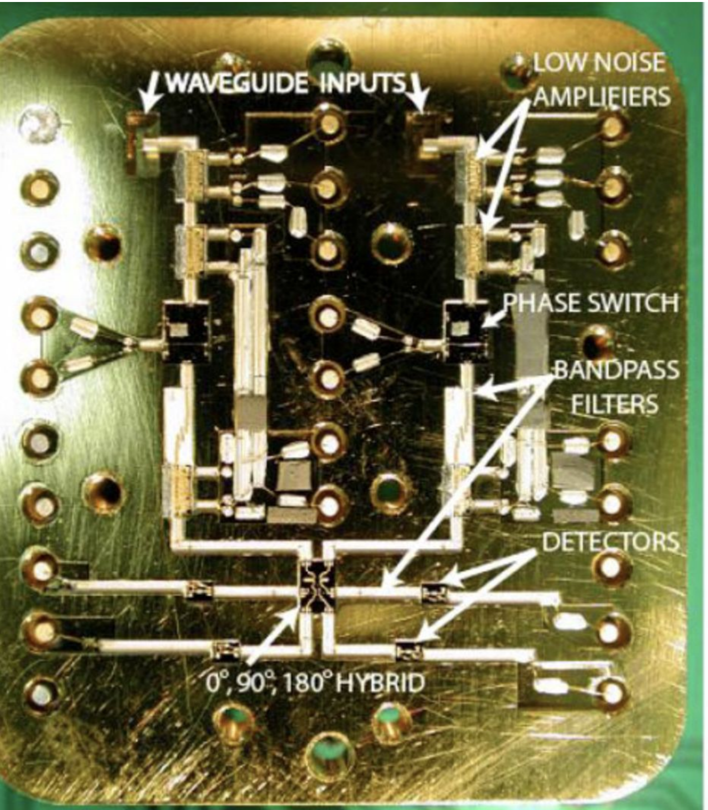
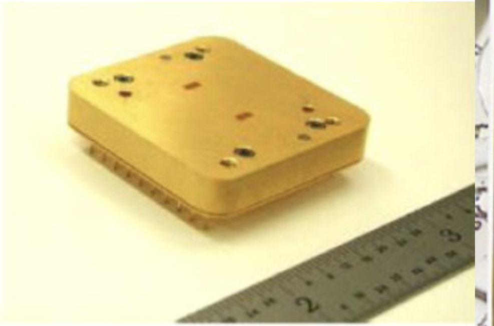
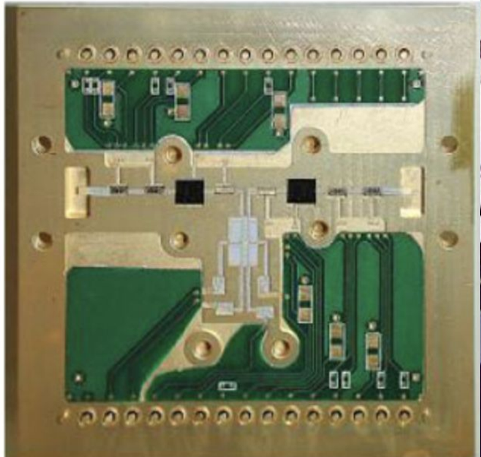
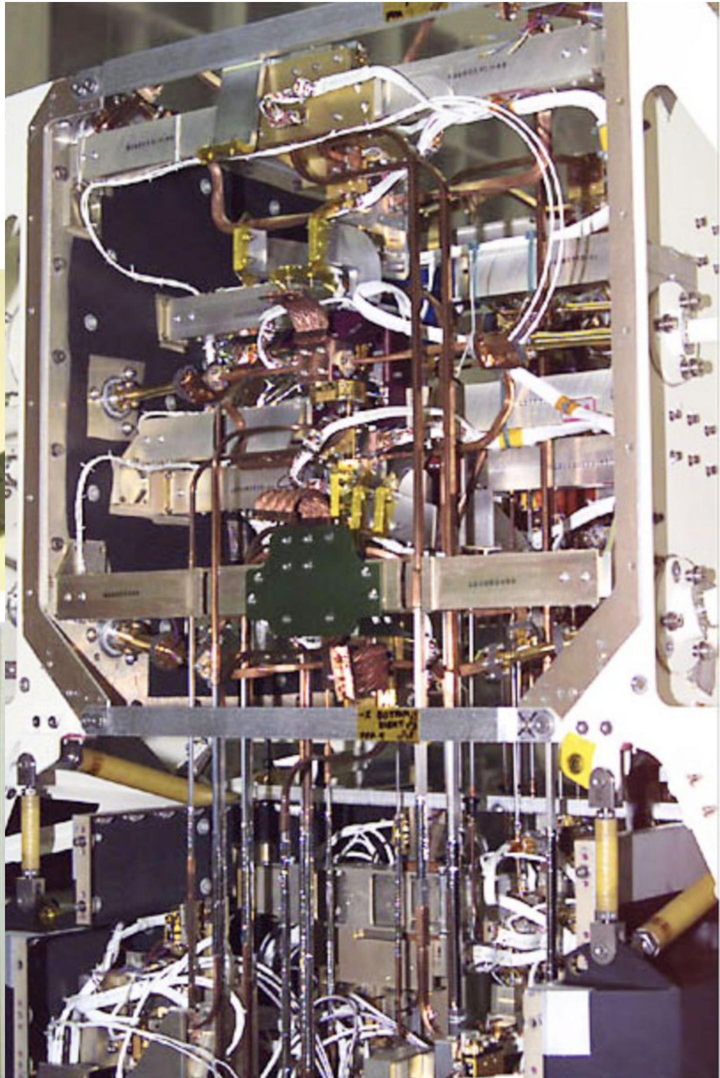
Coherent Methods and Receivers

Jeff McMahon









Overview

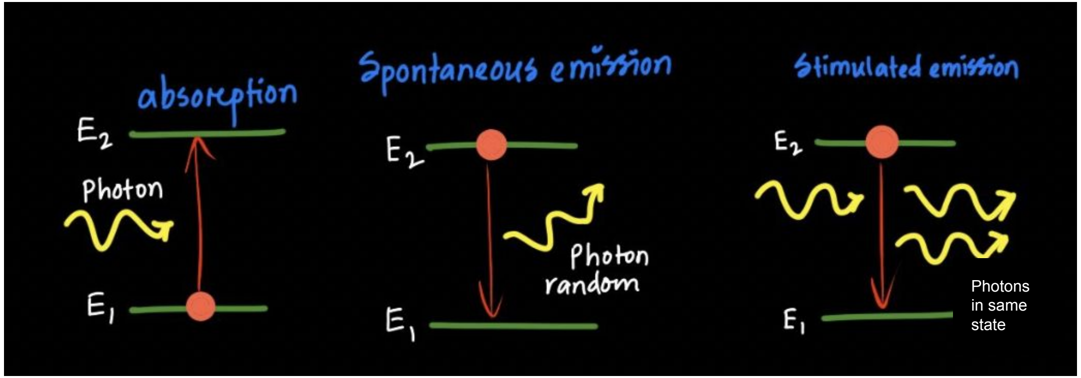
Almost without exception, every observation in astronomy and cosmology is rooted our ability to manipulate and detect electromagnetic radiation (light).

Light is a wave: $\vec{E} = \vec{E}_0 \sin(\vec{k} \cdot \vec{r} - \omega t + \phi)$

Coherent methods provide us with tools for directly manipulating the field of the incoming light, especially the amplitude and phase.

Amplifiers: understanding when coherent methods are appropriate

Because photons are bosons, passing these particles through a system with couplings to light can use stimulated emission to make copies of the incoming photon(s) with exactly the same state. This is amplification.



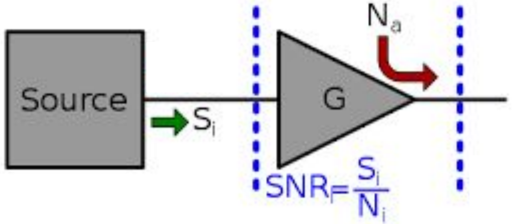
Quantum Mechanics adds noise

- This can be derived from the uncertainty principle ([see section titled linear amplification]())
- Alternatively we can understand this a competition between spontaneous and stimulated emission, with the spontaneous emission adding noise
    - This (beautiful) calculation provides an estimate of the signal to noise

$$SNR = N = \frac{1}{e^{h\nu/kT} - 1}$$

    - The S/N is high where the occupancy (N) is large
    - Since N is large at low frequencies, *amplifiers work well for low noise applications below about 100 GHz*
    - We will come back to quantifying this quantum limited noise after we talk calibration

Amplifiers: Noise



We discuss nose as if it were thermal and referred to the input of our amplifier or system.

- This is equivalent to finding the temperature of a black-body signal would you have to put into the input of the system to get the same amount power as the noise at the output of the amplifier.

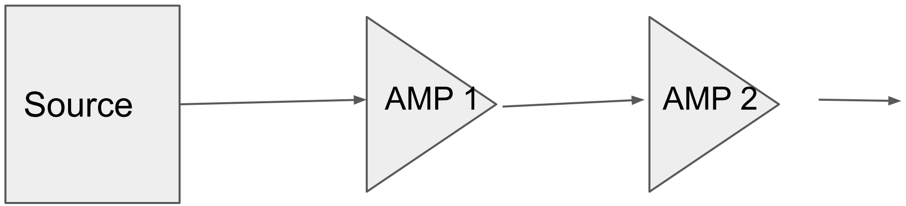
With this calibration the quantum limit can be estimated as:

$$T_{noise} \approx 4.8K \left(\frac{\nu}{100\ GHz} \right)$$

A rule of thumb is that ~3x the quantum limit represents about what is practically possible

- At 100 GHz this corresponds to about 15K
- At lower frequencies the performance improves which is why coherent techniques are favored especially below 50 GHz.

Noise in an amplification chain



For practical reasons a receiver may have multiple amplifiers

The noise in the first amplifier matters most!

- We want to design receivers to amplify as early as possible to minimize noise
- Loss before this amplification costs noise
- Analysis of other components follows similar logic

Component	Source	AMP 1	AMP 2
Gain	-	G1	G2
Noise	-	T1	T2
Output	S	G1(S + T1)	G2 G1 (S+T1) +G2 T2
output, referred to the input	S	S + T1	S + T1 + T2/G1 **= Tsys**
noise, referred to the input	-	T1	T1 + T2/G1

Instantaneous sensitivity

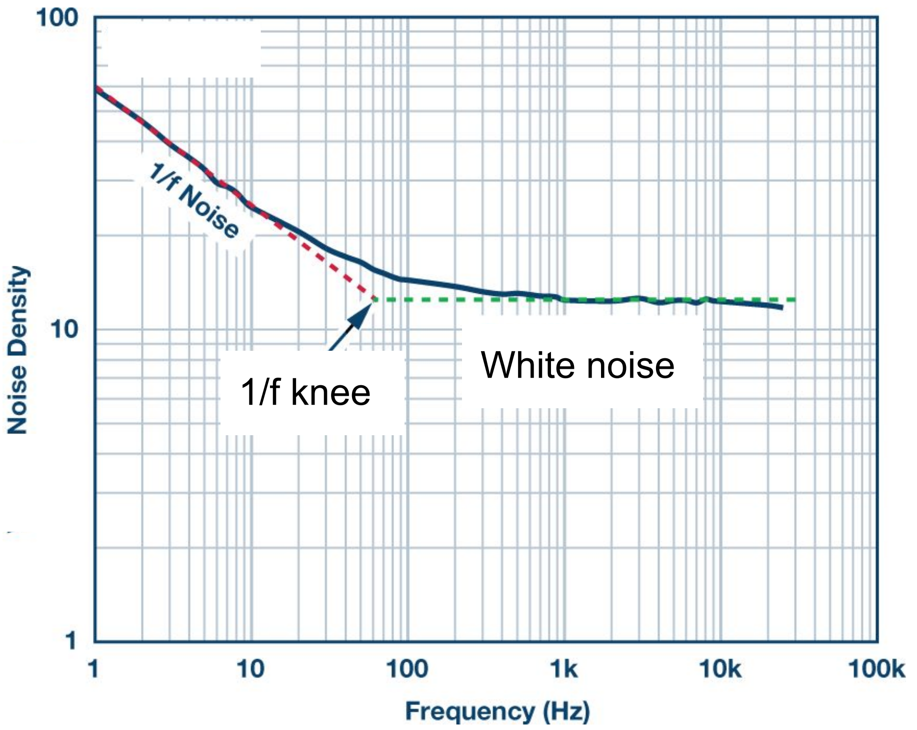
A useful metric is the 1 sigma error bar on a measurement after 1 second of integration.   We can call this the instantaneous sensitivity S:

$$S = \frac{T_{sys}}{\sqrt{\Delta\nu}}$$

- T_sys is the system temperature, refered to the input from the previous slide
- $\Delta\nu$ Is the bandwidth (e.g., the range of frequencies that pass through the receiver)
- **Exercise:** estimate the instantaneous sensitivity of a 100 GHz receiver with 15 GHz of bandwidth. Express your answer in units of uk-sqrt(s)
  - Follow on question: how long does it take to get a 1 nK uncertainty with this system?

Amplifiers: low frequency noise

- Sadly, life isn't easy.
- One manifestation of this truth is low frequency noise which is also called 1/f noise (a specific case), or pink noise.
- The plot to the right shows a typical example
- This noise is a ubiquitous feature to most detection systems
- Knee-frequencies for amplifiers are typically ~100 Hz
- Much of receiver design is geared towards introducing modulation to avoid this noise (more in the examples)
- **Exercise:** Compute the noise (1 s integration) of the 100 GHz receiver from the previous slide if the first amplifier has a 1/f knee of 100 Hz.

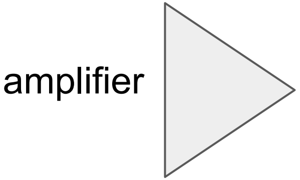


Understanding receiver systems:

a guide to useful components

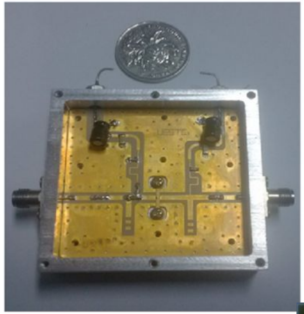
Coherent components: Amplifiers

Block diagram symbol



One realization is a transistor amplifier, specifically a High Electron Mobility Transistor or HEMT. If this is a monolithic (rather than discrete system is is called a MMIC (monoloythic microwave integrated circuit)

- You connect the transistor to a power supply, bias the gate, and then the input signal releases a larger signal at the output
- characteristics
    - G
        - the gain
    - T_noise
        - the noise temperature
    - 1/f- knee
        - The frequency where the 1/f becomes important
    - P_1dB:
        - If the input signal is too large the amplifier will no longer be linear and the effective gain falls off. This parameter specifies the input power at which the gain the gain falls by 1dB = 10^{-.1} which is 20% below the linear prediction. This effect is called compression and should be avoided
    - Negative return loss
        - This is an example of a non-ideality
        - Amplifiers can send a fraction of the amplified signal back out the input– this can cause surprising problems on occasion
- For reference there are two main types
    - low noise amplifiers (LNAs) optimized for low noise, and
    - power amplifiers optimized for a high output power



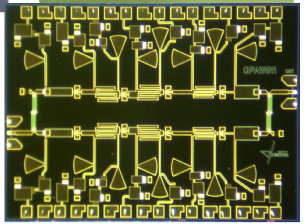


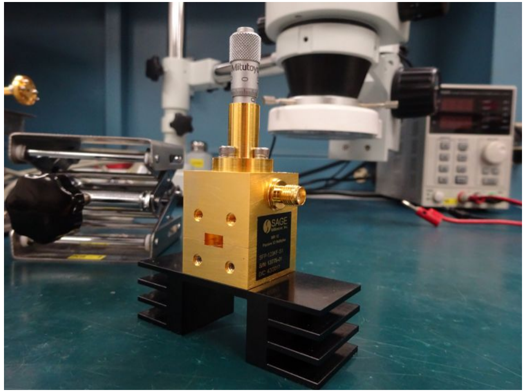
Fig. 2. GaAs W-band MMIC. The MMIC is configured as a 4-Stage,

Example amplifiers

Coherent components: Local Oscillator (aka and LO)

- Provides a constant tone at relatively high power
- Key parameters
  - P
    - Power
  - f_0
    - Frequency
    - Perhaps also tuning range
  - Phase stability
    - This is related to the narrowness of the tone– these are extremely narrow band signals
- Types
  - Gunn oscillator (high stability)
  - IMPATT oscillator (high power)
  - Crystal oscillators (can be stabalized and multiplied up)

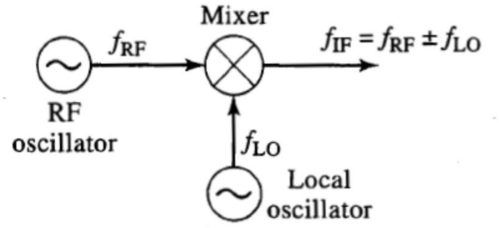
Block diagram symbol

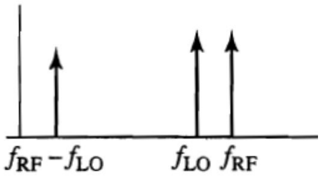


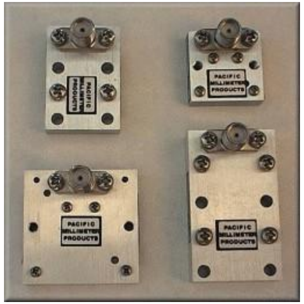
Coherent components: Mixers

- Mixers work on the principle of beat frequencies
  - Typical implementation– one or mode diodes that are biased on and off by the local oscillator power
- This allows you to shift signals to lower frequencies where they are easier to manipulate, digitize, etc.
- Mixers take two inputs
  - RF signal
    - Radio frequency
  - LO signals
    - Local oscillator
- Produces on output
  - IF
    - Interference frequency
      - f_IF = f_RF-f_LO
- Key parameters
  - Conversion loss
    - How much input power is lost in the conversion
  - LO power range
    - too much LO power breaks it, too little it won’t turn on
  - P1dB
    - Too much RF will make the device go non-linear
  - Noise
    - Typically pretty high– usually these placed after amplifiers
    - Expressed in T_noise
- Types of mixers
  - [Subharmonic mixers](#) (low noise)
  - [Fundamental mixers](#) (works on first harmonic OK noise, conversion loss)
  - [Harmonic mixers](#) (high noise / high conversion loss, but super easy to work with)

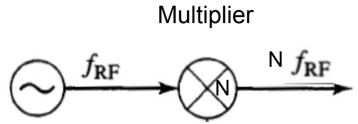
Block diagram symbol





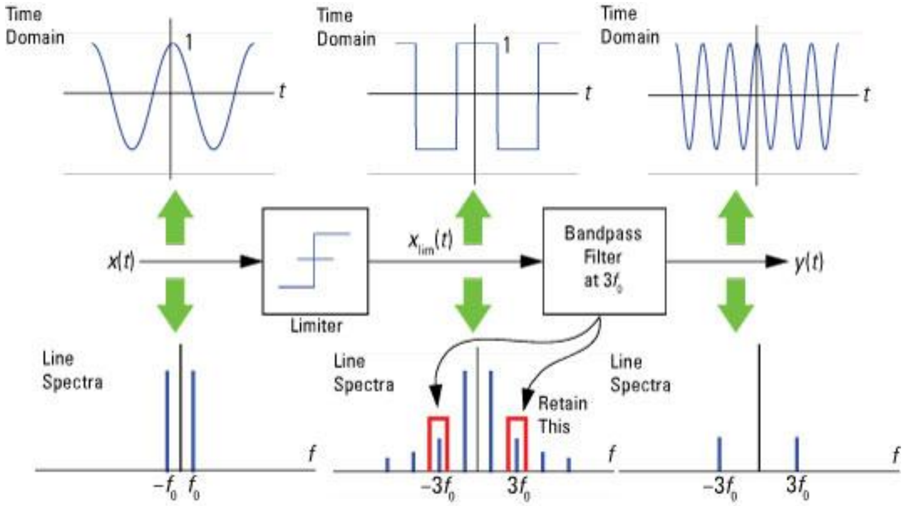


Coherent components: Multipliers



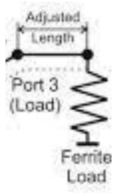
Multipliers are devices which convert a sine wave into a square (or square like) wave– in harmonic space this leads higher frequency components (integer multiples of the input frequency

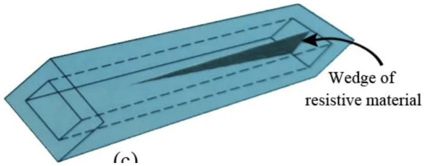
- Can double, triple, etc the input
- Are often useful for producing high frequency signals from low frequency LOs
- Implementation– one or more diodes
- Key parameters
  - Input power range
  - Conversion loss
  - Operating harmonics
- Examples
  - [Pacific millimeter]
  - [Virginia Diodes]



Coherent components: Terminators

- These are components which can absorb signals
- Realizations of of this component include:
    - a matched resistor in electronics,
    - An adiabatic absorber in free space (eccosorb),
    - An adiabatic absorber in wave guide,
    - Etc
- Key parameters
    - Temperature (these emit and absorb)
    - Reflection (ideally this would be zero, it isn't and deviations can be important)



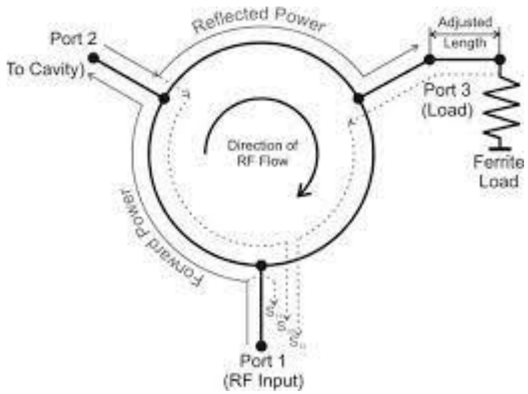


Coherent components: Isolators and Circulators

A **circulator** is a 3 port device where

- Port 1 couples to Port 2
- Port 2 couples to Port 3
- Port 3 couples to Port 1
- Other couplings are suppressed

These can be made using ferrite loaded components to create a preferred direciton

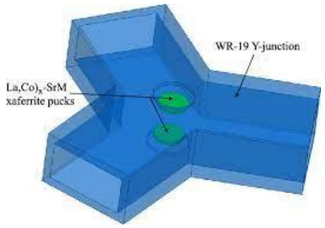


If port 3 is terminated you get an **isolator**

- Port 1 is coupled to port 2
- Port 2 doesn't couple well to port 1

A key parameter is the "isolation" which gives the coupling between ports 2 and 1

These are useful in eliminating negative return loss and otherwise ensuring that signals only go where they should



Coherent components: Phase Switches

Modulate the phase of the incoming light by +/- 180º (some other factor)

Can be realized by switching a component of different path length in and out of a system, or equivalent tricks

This is a very useful component for introducing high frequency modulation to avoid 1/f noise

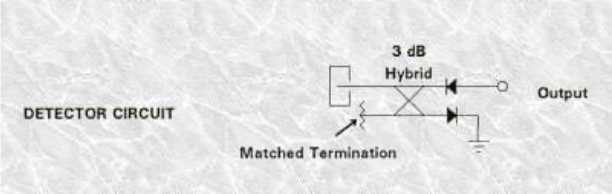
Coherent components: Detector Diodes

Detect an RF signal and convert it to a voltage

One or more diodes to rectify the singal are an example of an implementation

Key parameters

- Responsivity expressed as a ratio of voltage to power
- P1dB (these compress)
- Noise



Coherent components: Passive components

Hybrid coupler

- Two inputs, two outputs
  - Inputs labeled A and B
  - Outus can be designed to be A+B and A-B in a 180º coupler, or
    - A + iB and A- iB in a 90º coupler

Cross-guide coupler

- Couple a small amount (~ -30 dB) from one wave guide into another

Band-pass filters

- Select and reject wanted and unwanted frequencies

Ortho-mode transducers

- separates linear (or circular) polarization

Diplexer

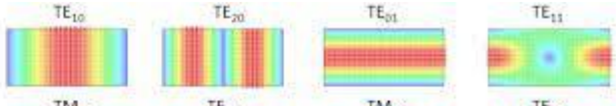
- Combines (or separates) two signals into a single output (input)
- Combines an LO and IF onto a single input to a mixer

And many many more…

Coherent components: Wave Guides

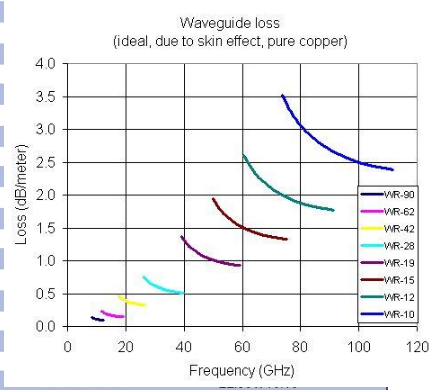
A key component for coherent systems is wave guides

- These tend to have 1.5:1 ratio bandwidth
    - Above an octave 2:1 bandwidth these become multi-moded complicating their use.
- The table to the right gives the various naming conventions for the standard types of waveguide.
- Silver and copper waveguide are low loss.
- stainless guide is often needed for thermal isolation– it is significantly lossier



Waveguide Frequency Bands with Interior Dimensions

Frequency Band	Waveguide Standard	Frequency Limits (GHz)	Inside Dimensions (inches)	Inside Dimensions (mm)
	WR-2300	0.32 - 0.49	23.000 x 11.500	584.2 x 292.1
	WR-2100	0.35 - 0.53		
	WR-1800	0.43 - 0.62		
	WR-1500	0.49 - 0.74		
	WR-1150	0.64 - 0.96		
	WR-1000	0.75 - 1.1		
	WR-770	0.96 - 1.5		
	WR-650	1.12 to 1.70		
R band	WR-430	1.70 to 2.60		
D band	WR-340	2.20 to 3.30		
S band	WR-284	2.60 to 3.95		
E band	WR-229	3.30 to 4.90		
G band	WR-187	3.95 to 5.85		
F band	WR-159	4.90 to 7.05		
C band	WR-137	5.85 to 8.20		
H band	WR-112	7.05 to 10.00		
X band	WR-90	8.2 to 12.4		
X-Ku band	WR-75	10.0 to 15.0	0.750 x 0.375	19.05 x 9.525
Ku band	WR-62	12.4 to 18.0	0.622 x 0.311	15.7988 x 7.8994
K band	WR-51	15.0 to 22.0	0.510 x 0.255	12.954 x 6.477
K band	WR-42	18.0 to 26.5	0.420 x 0.170	10.668 x 4.318
Ka band	WR-28	26.5 to 40.0	0.280 x 0.140	7.112 x 3.556
Q band	WR-22	33 to 50	0.224 x 0.112	5.6896 x 2.8448
U band	WR-19	40 to 60	0.188 x 0.094	4.7752 x 2.3876
V band	WR-15	50 to 75	0.148 x 0.074	3.7592 x 1.8796
E band	WR-12	60 to 90	0.122 x 0.061	3.0988 x 1.5494
W band	WR-10	75 to 110	0.100 x 0.050	2.54 x 1.27
F band	WR-8	90 to 140	0.080 x 0.040	2.032 x 1.016
D band	WR-6	110 to 170	0.0650 x 0.0325	1.651 x 0.8255
G band	WR-5	140 to 220	0.0510 x 0.0255	1.2954 x 0.6477
	WR-4	170 to 260	0.0430 x 0.0215	1.0922 x 0.5461
	WR-3	220 to 325	0.0340 x 0.0170	0.8636 x 0.4318
Y-band	WR-2	325 to 500	0.0200 x 0.0100	0.508 x 0.254
	WR-1.5	500 to 750	0.0150 x 0.0075	0.381 x 0.1905
	WR-1	750 to 1100	0.0100 x 0.0050	0.254 x0.127



Coherent components: Coaxial Cables

No lower cuttoff frequency

The cutoff frequency applies to the start of the next mode this means that at high frequencies coaxes need to be relatively small

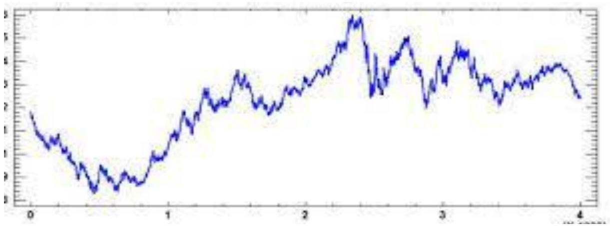
There are a large number of different connectors for these

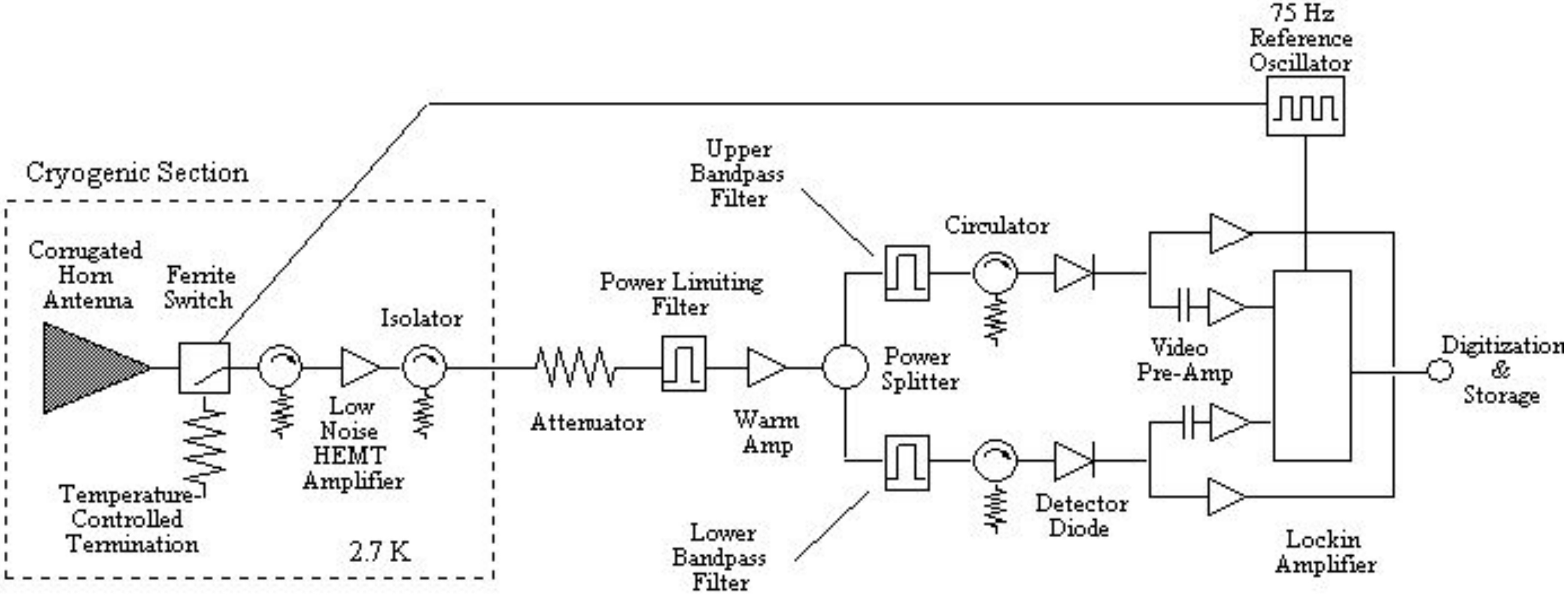
- SMA, SMB, 2.92 mm (aka K), etc. many look the same (eg K and SMA)
- but be sure not to connect between different standards without an adapter– this could cause damage

Understanding receiver systems:
examples

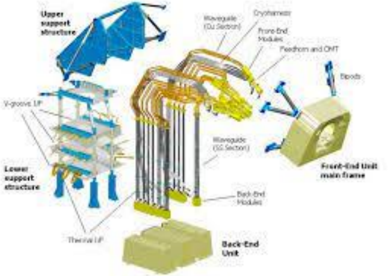
Example: ARCADE

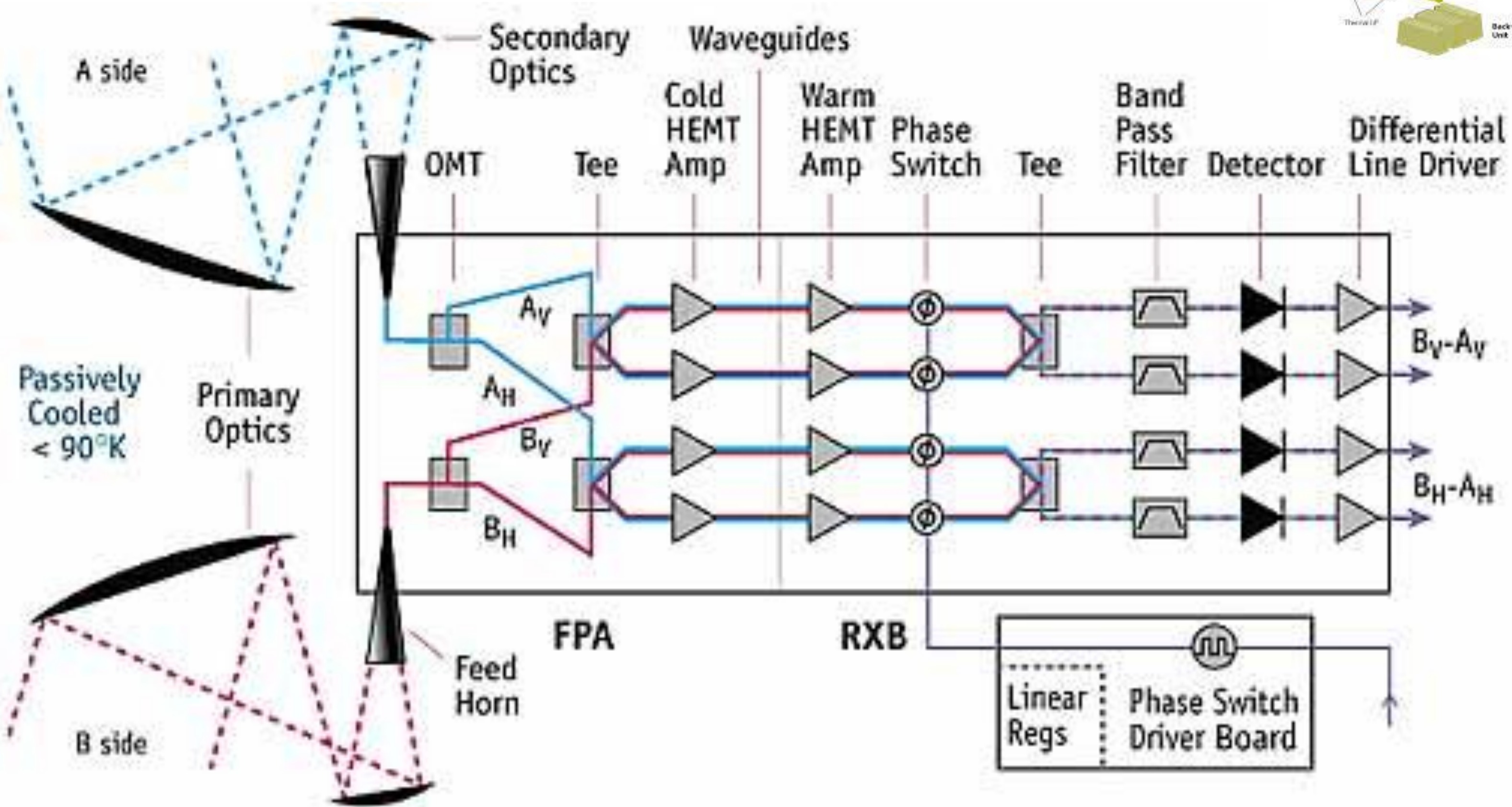
(ARCADE made a measurement of the absolute CMB Temperature at low frequencies)



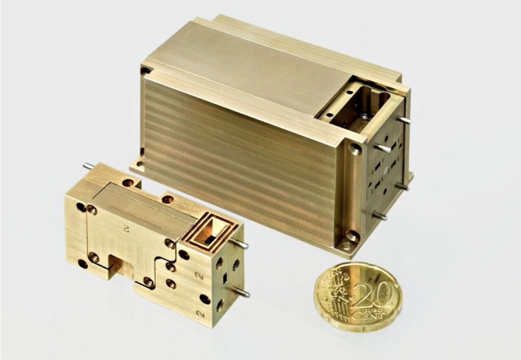


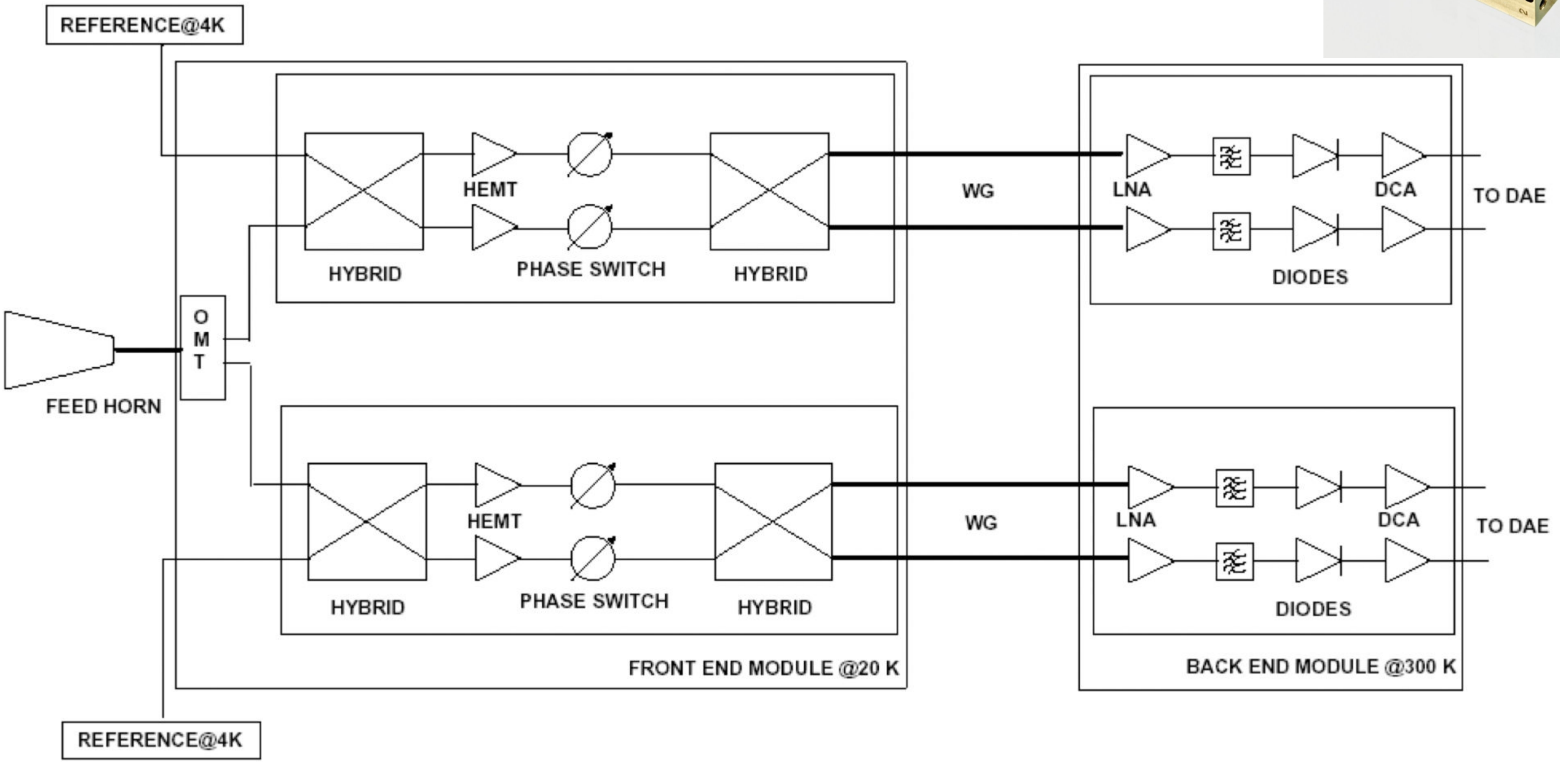
Example: WMAP (CMB satellite)



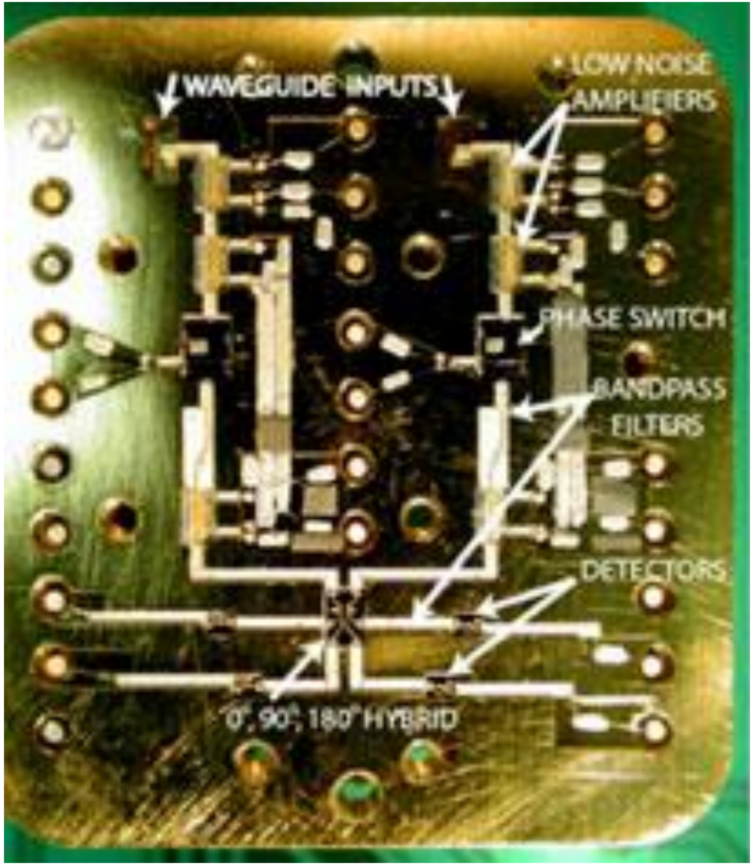


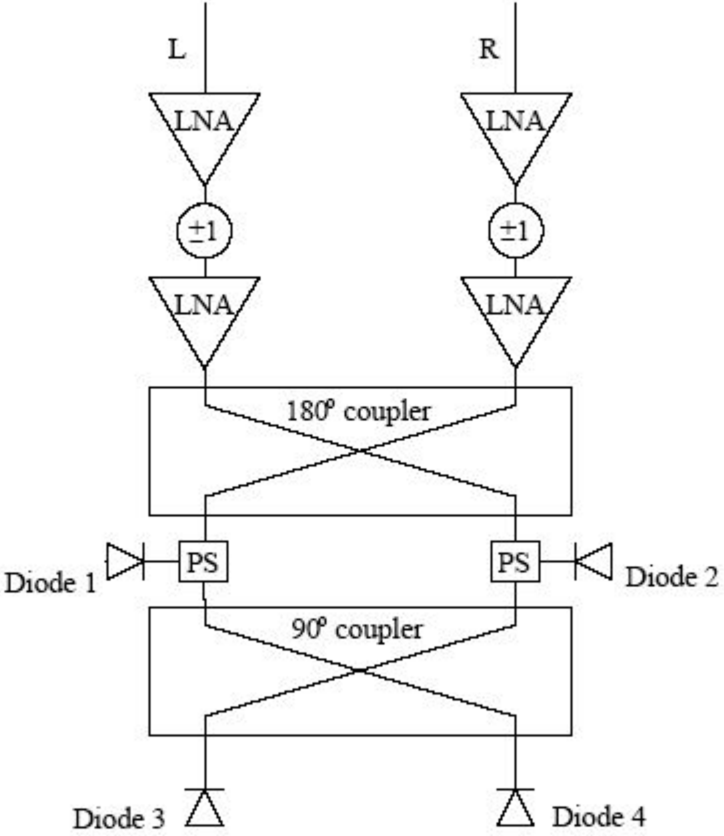
Planck LFI, Example: 70 GHz band



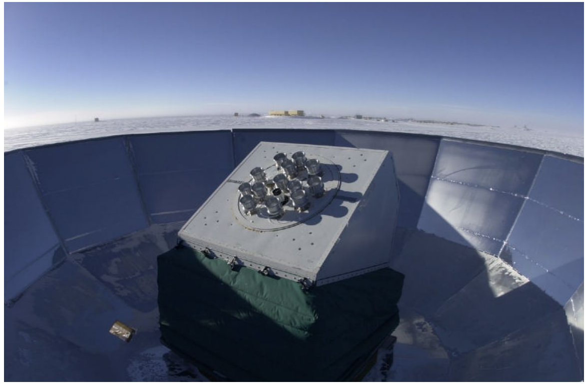


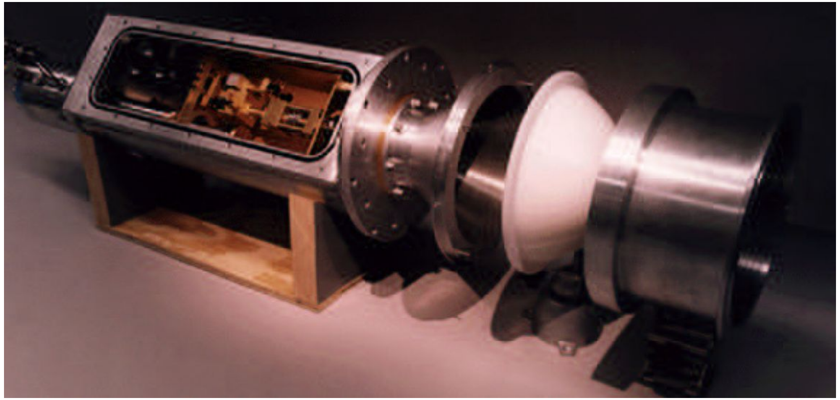
Example: QUIET (CMB polarimeters)

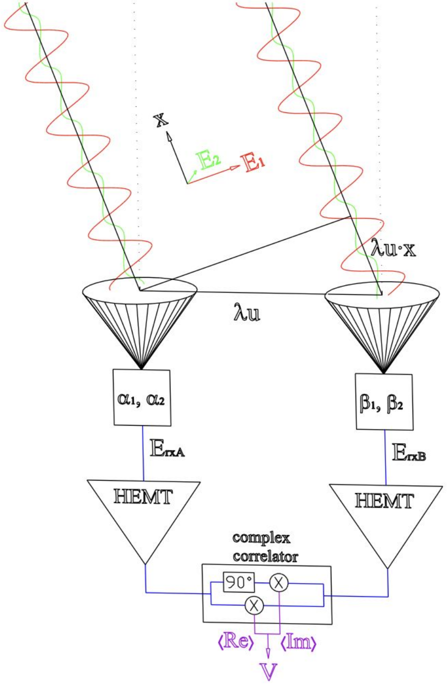




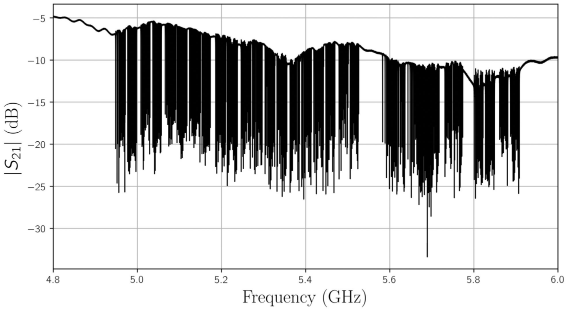
Example: DASI (CMB interferometer, polarizaiton)



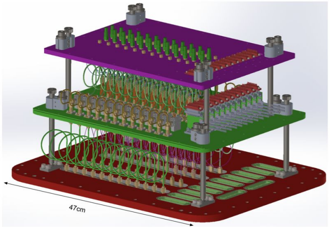




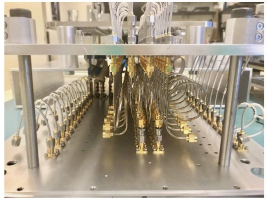
Example: SMURF
(The detector readout for SO)



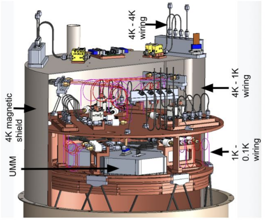
(a) SO wiring design



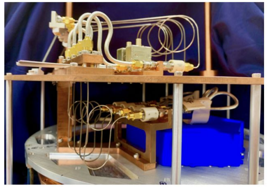
(b) URH design



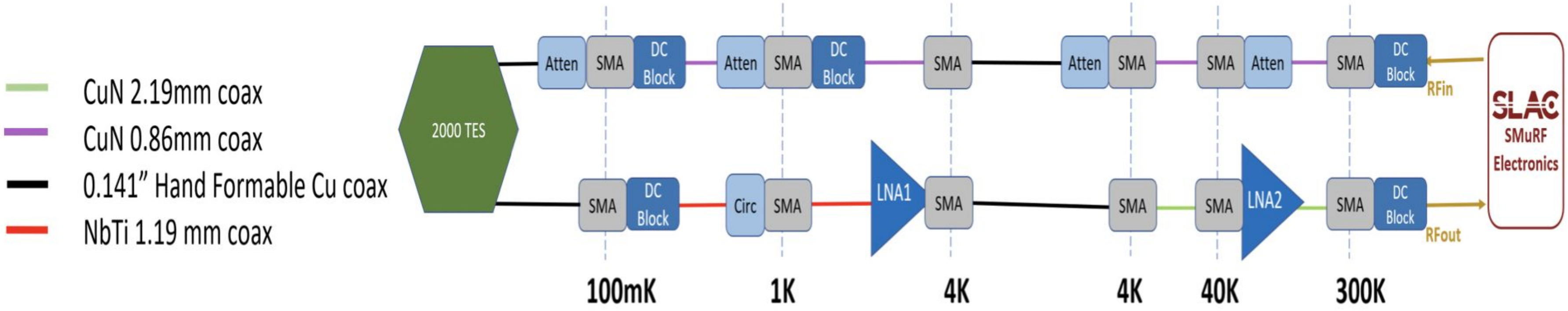
(c) Wiring in URH during assembly



(d) Cross section view of LATR cold wiring design



(e) LATR cold readout wiring prototype



(a) SO wiring design