M I D E M 2 0 1 5

51st International Conference on Microelectronics, Devices and Materials with the Workshop on Terahertz and Microwave Systems

MILLIMETER SOURCES

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Hotel Golf, Bled, Slovenia,
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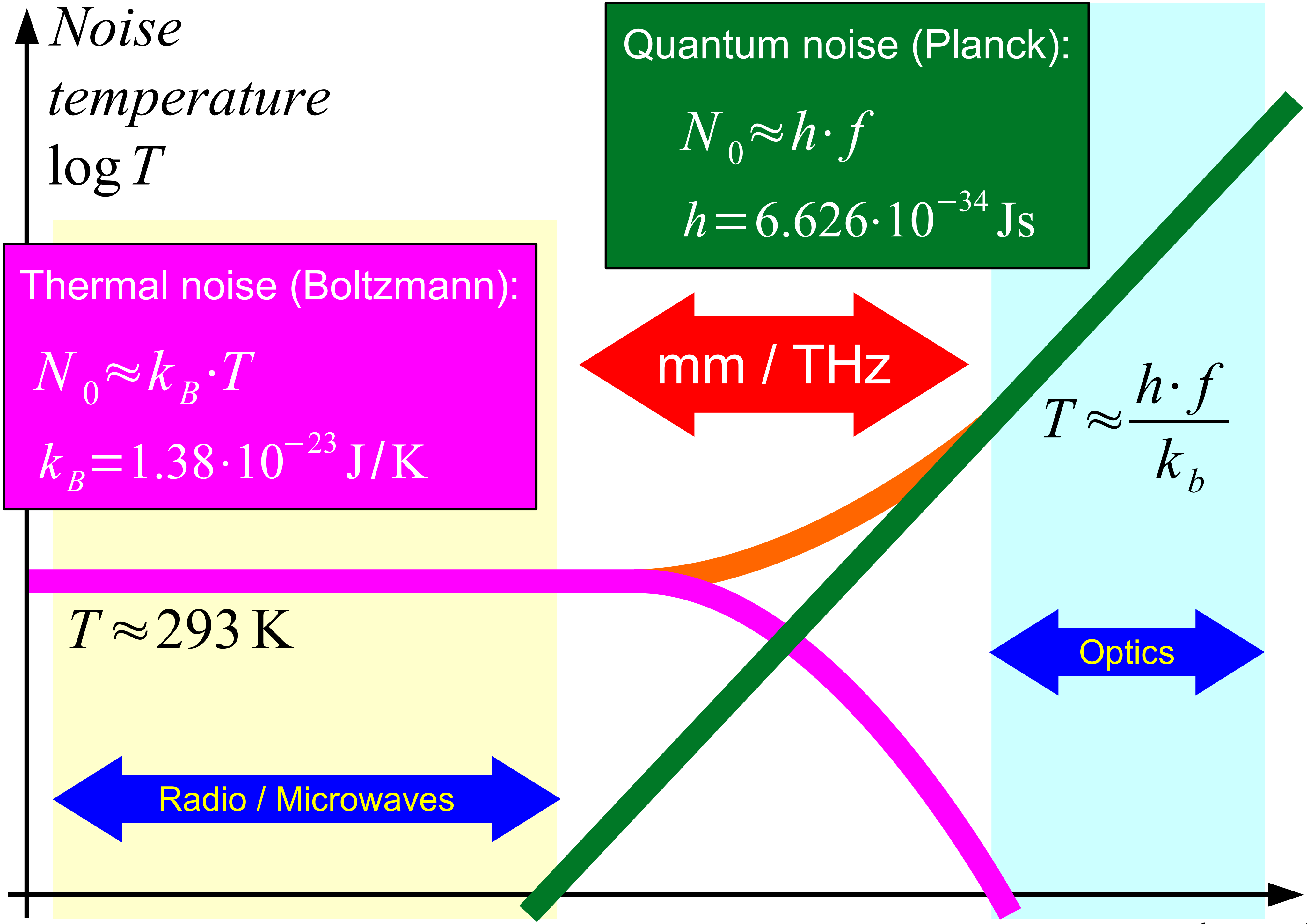
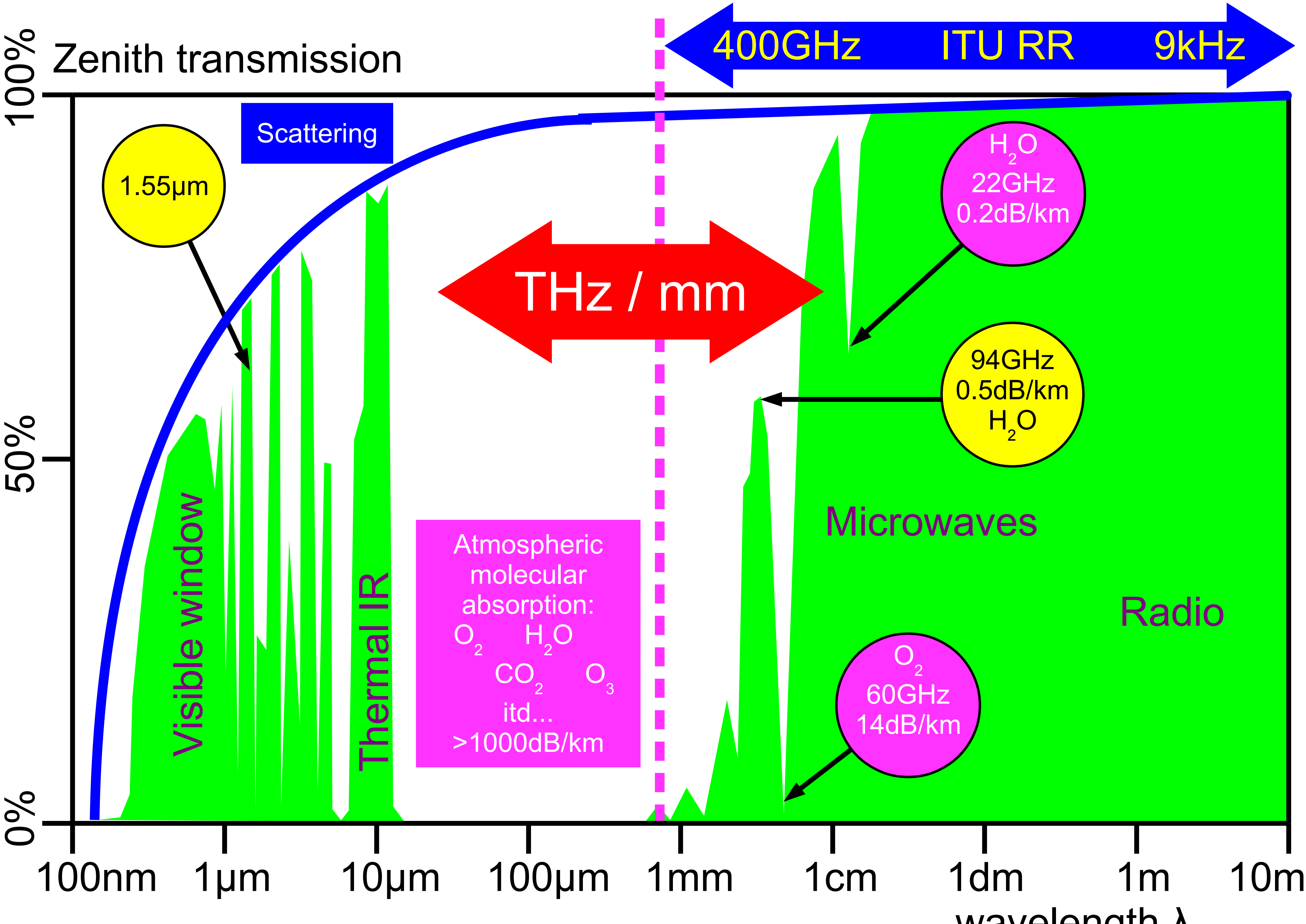
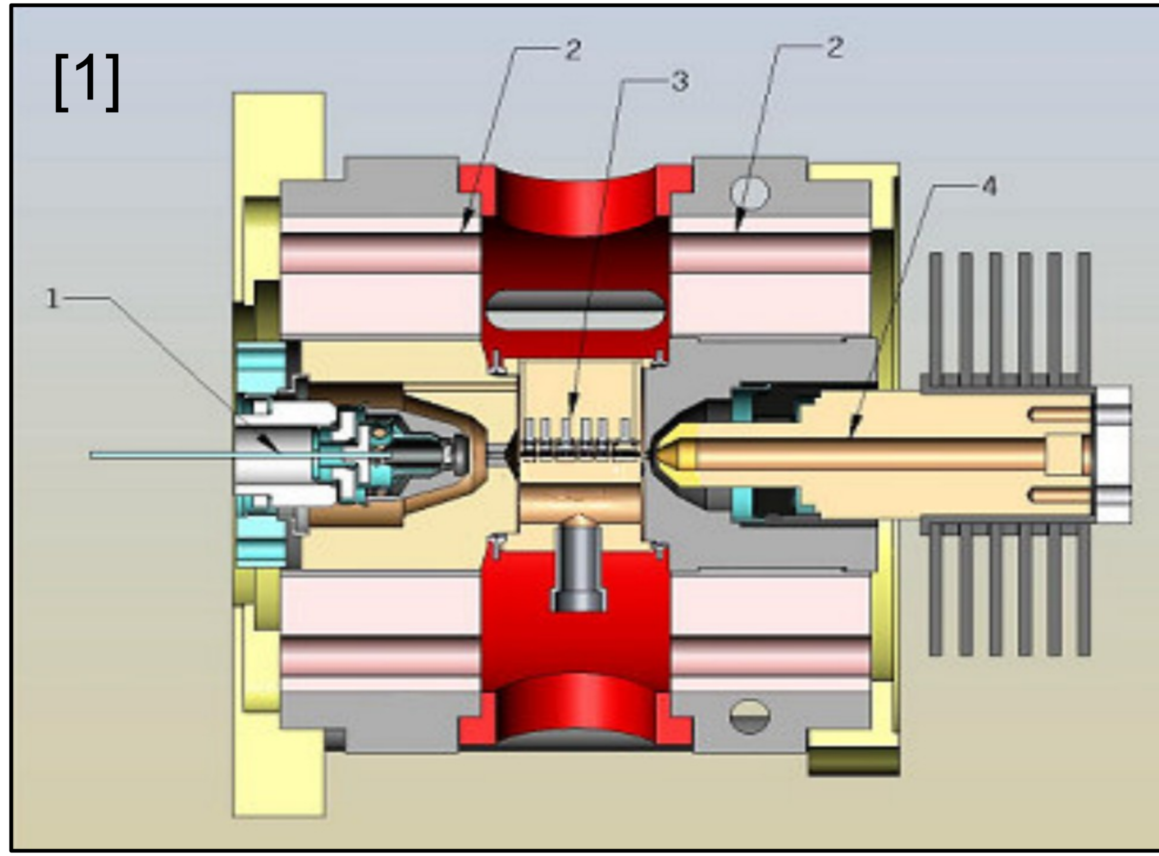
List of slides: MILLIMETER SOURCES



1 - Noise spectral density



2 - Atmospheric attenuation



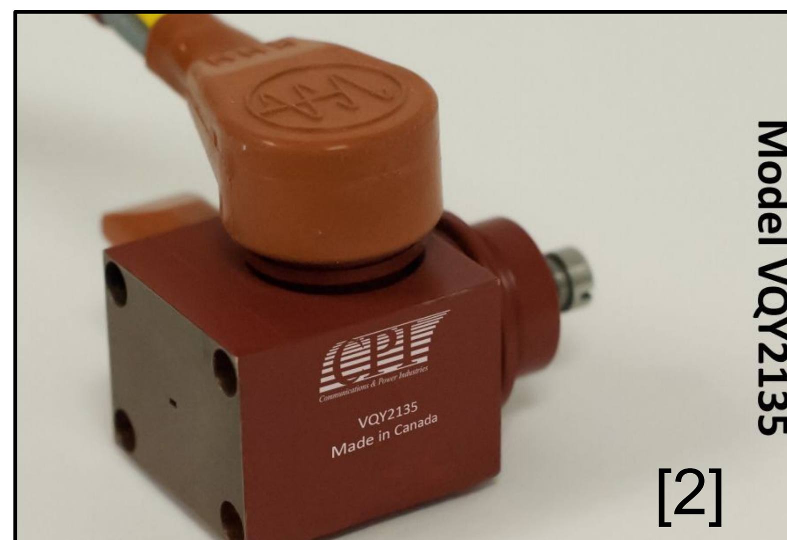
Slow-wave vacuum tube

Narrowband electronically tunable (voltage U)

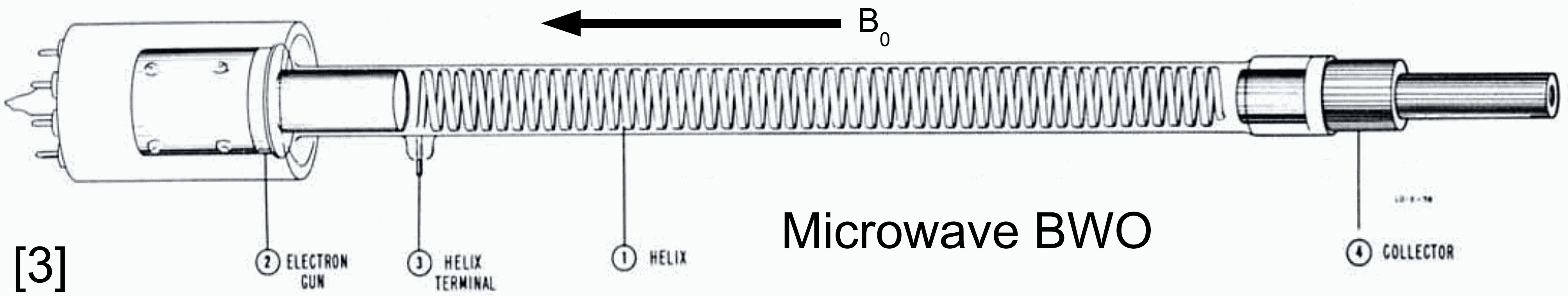
Typical data:
$f_0 = 300$ GHz
$\Delta f = +/-0.2$ GHz
$P_{OUT} = 50...500$ mW
$I = 80$ mA
$U = 10.7...11.2$ kV
air / contact cooling

mm EIO

1 el. gun
2 magnet
3 cavities
4 collector



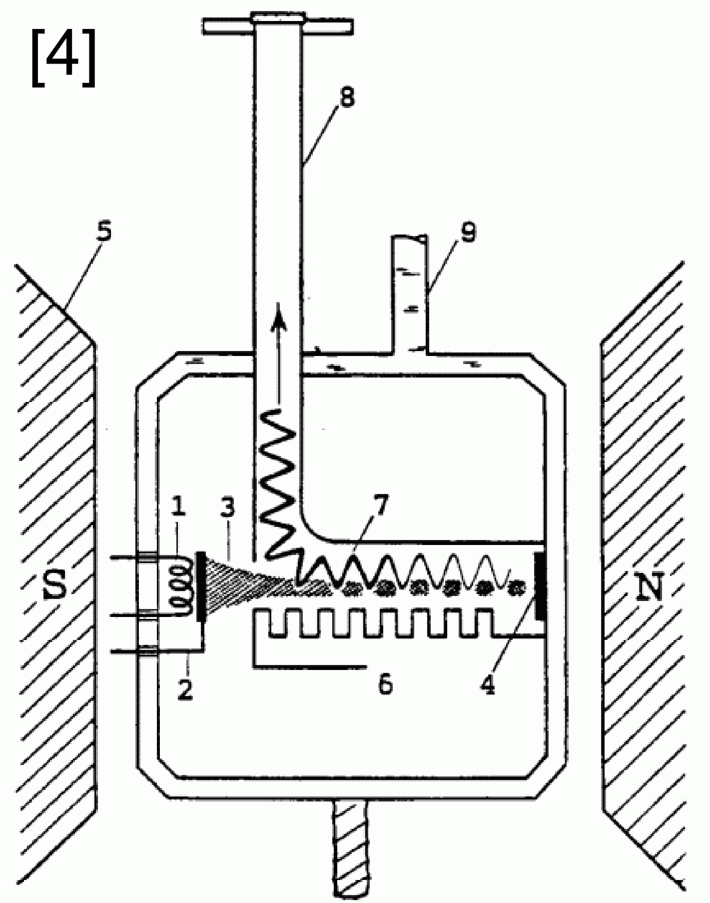
3 - Extended Interaction Klystron / Oscillator (EIK / EIO)



Slow-wave vacuum tube

Wideband electronically tunable (voltage U)

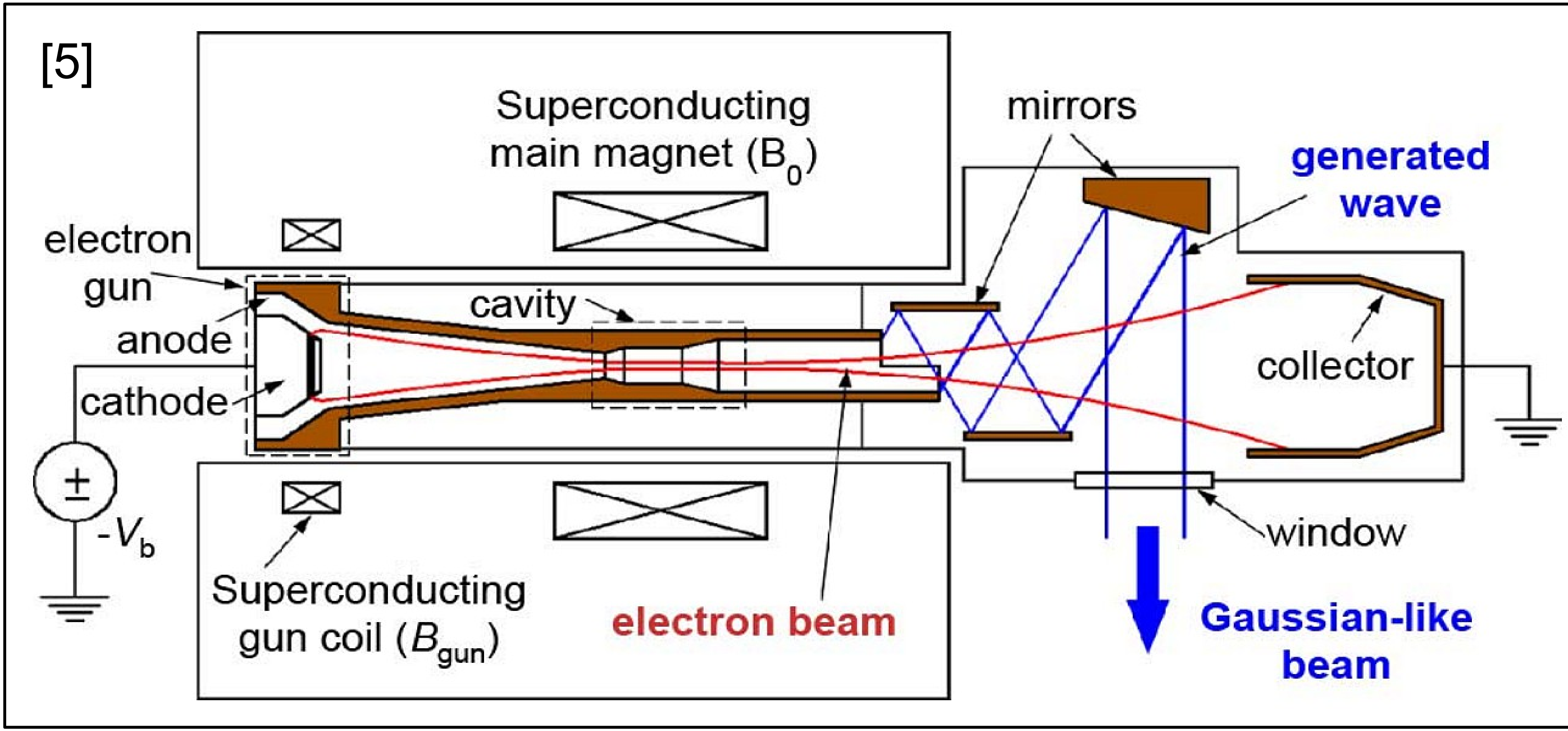
Typical data:
$f = 258...375$ GHz
$P_{OUT} = 1...10$ mW
$I = 25...40$ mA
$U = 1...4$ kV
$B_0 = 0.7T$
water cooling



mm BWO

1 heater
2 cathode
3 el. beam
4 collector
5 magnet
6 SWS
7 EM wave
8 waveguide
9 water cooling

4 - Bacward-Wave Oscillator (BWO or Carcinotron)

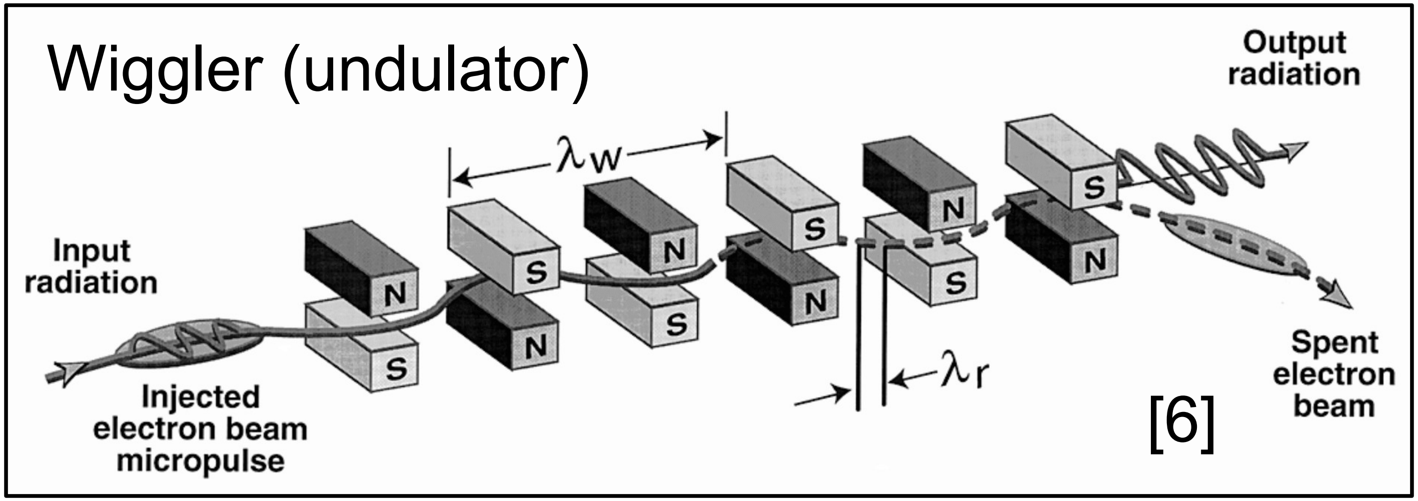


$$f = \frac{|Q_e| B_0}{2\pi m_e}$$

$$B_0 \approx \frac{1\,\text{Tesla}}{28\,\text{GHz}} \cdot f$$

Fast-wave vacuum tube
High power $P_{OUT} \approx 1$ MW
Wideband tunable (U & B_0)
Generation of mm waves requires:
1) superconducting magnets
2) harmonic operation

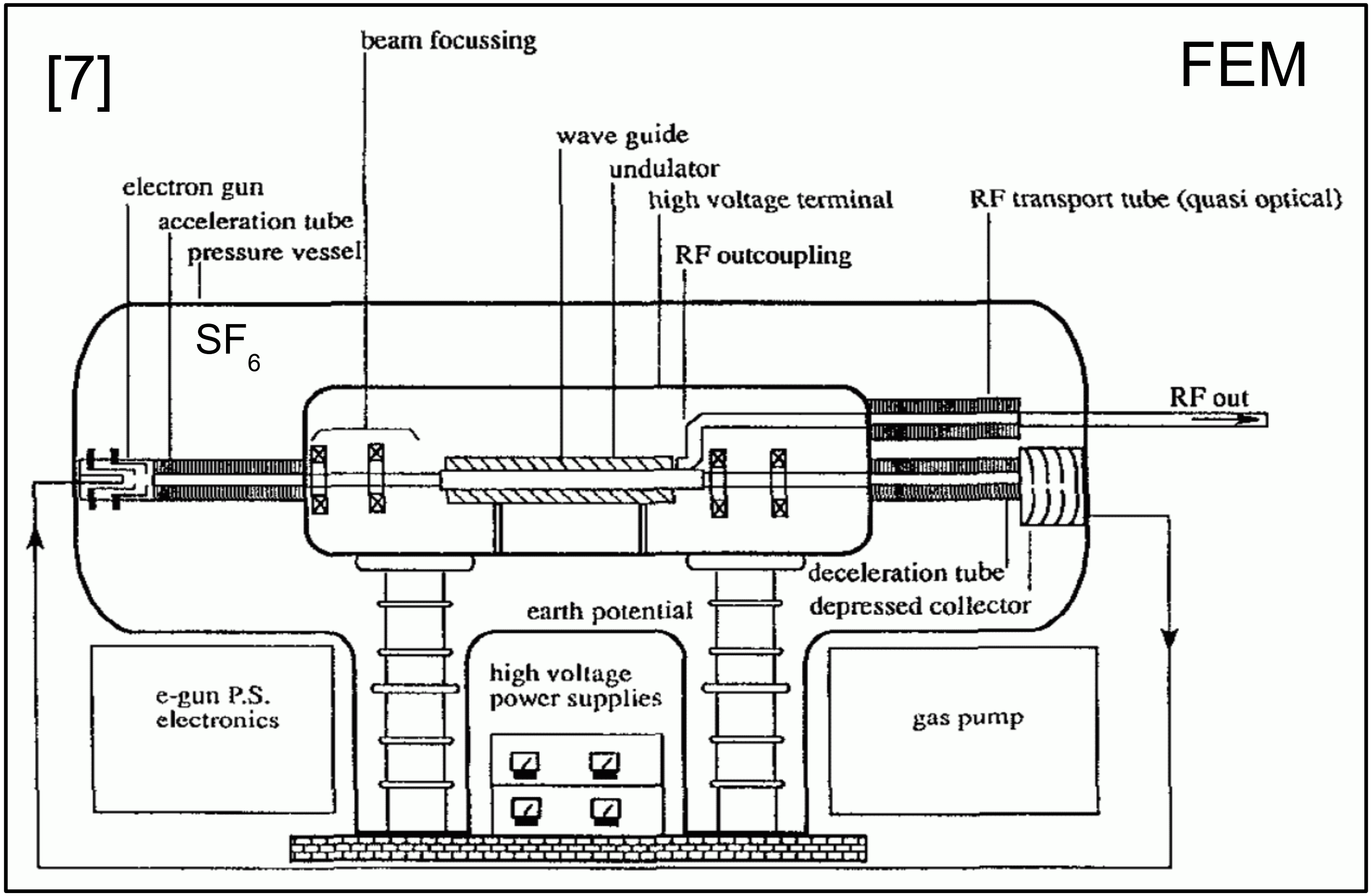
5 - Gyrotron



$$\lambda_r \approx \frac{\lambda_w}{2\gamma^2}$$

Lorentz

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$



Fast-wave vacuum device

High power
$P_{OUT} \approx 1$ MW

Widely tunable (U)

Amplification of mm waves requires
$U \approx 2...6$ MV

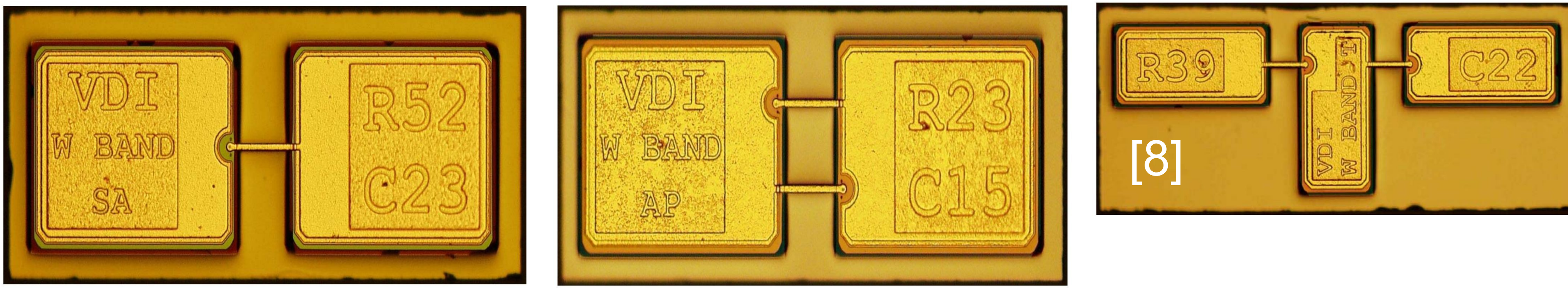
6 - Free-Electron Laser (FEL) or Maser (FEM)

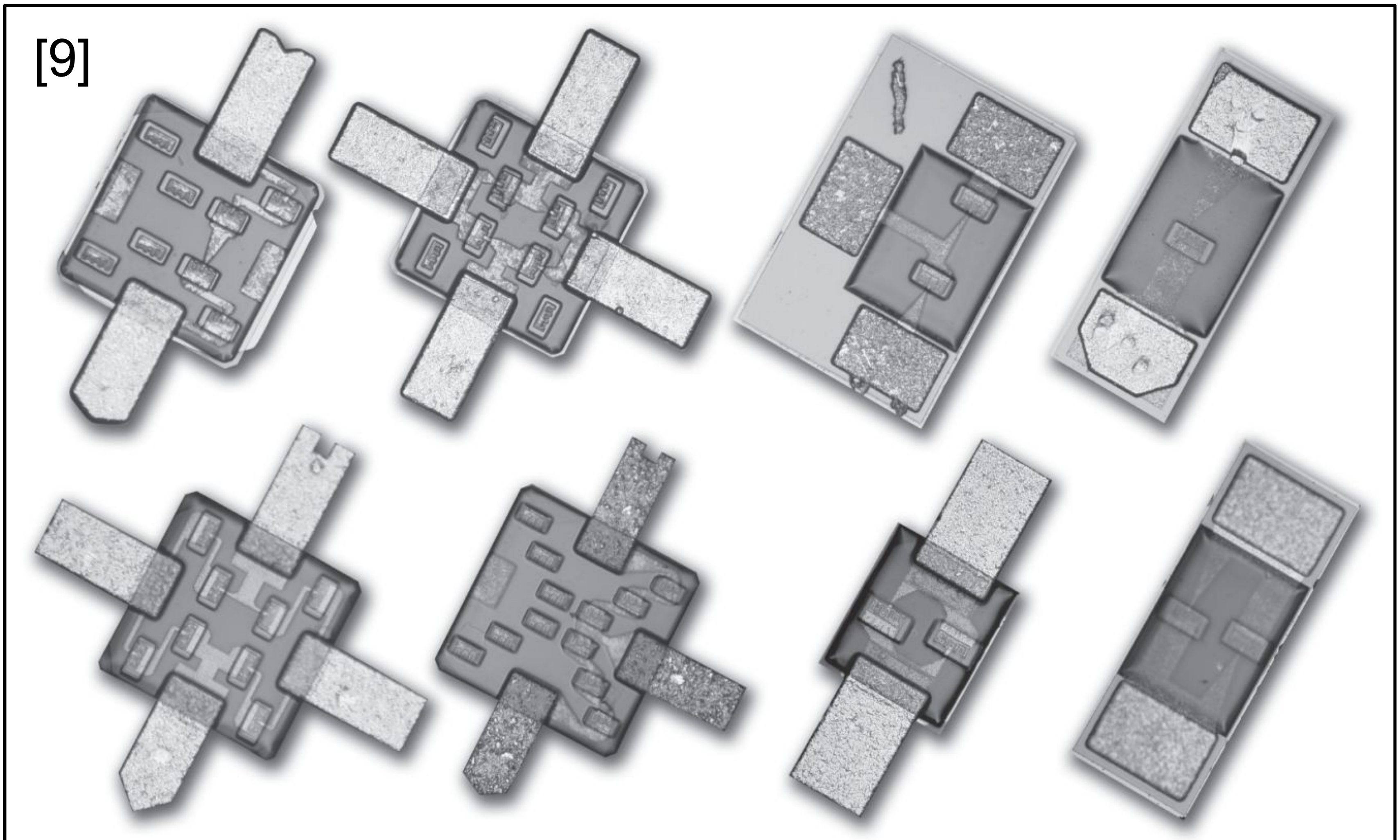
Semiconductor	Bandgap ΔW [eV]	Dielectric strength E_{MAX} [V/cm]	Electron mobility μ_n [cm²/Vs]	Hole mobility μ_p [cm²/Vs]
PbS	0.37	(breakdown<2V)	600	200
Se	1.95	(breakdown<25V)	0.005	0.14
PbSe	0.27		900	700
PbTe	0.32		1700	930
Cu_2O	2.137	(breakdown<8V)	0.2	0.1
Si	1.11	$3 \cdot 10^5$	1400	450
Ge	0.67	10^5	3900	1900
$Si_{1-x}Ge_x$	0.67-1.11	$3 \cdot 10^5$		
SiO_2	9	10^6-10^7		
Si_3N_4	5.4	$3 \cdot 10^6$		
C (diamond)	5.5	10^6-10^7	2200	1800
3C-SiC	2.36	10^6	800	320
4H-SiC	3.23	$3 \cdot 10^6$-$5 \cdot 10^6$	900	120
6H-SiC	3.05	$3 \cdot 10^6$-$5 \cdot 10^6$	400	90
GaAs	1.43	$4 \cdot 10^5$	5000	400

7 - Electrical properties of semiconductors (1)

Semiconductor	Bandgap ΔW [eV]	Dielectric strength E_{MAX} [V/cm]	Electron mobility μ_n [cm^2/Vs]	Hole mobility μ_p [cm^2/Vs]
AlAs	2.16	$6 \cdot 10^5$	1200	420
$Ga_{1-x}Al_xAs$	1.43-2.16	$4 \cdot 10^5 - 6 \cdot 10^5$		
InP	1.344	$5 \cdot 10^5$	5400	200
GaP	2.26	10^6	250	150
GaSb	0.726	50000	3000	1000
InAs	0.354	40000	40000	400
InSb	0.17	1000	77000	850
GaN	3.4	$5 \cdot 10^6$	1800	30
AlN	6.28	$1.2 \cdot 10^6 - 1.8 \cdot 10^6$	300	14
InN	0.65		3200	
BN	5.4	$3 \cdot 10^6 - 6 \cdot 10^6$	200	500
CdS	2.42		400	
CdSe	1.74		650	
CdTe	1.44		1100	100
$Hg_{1-x}Cd_xTe$	0-1.5			

8 - Electrical properties of semiconductors (2)





$U_F \approx 0.7V$

$@I_F = 1mA$

$U_R \approx 5V ...$

$... 10V$

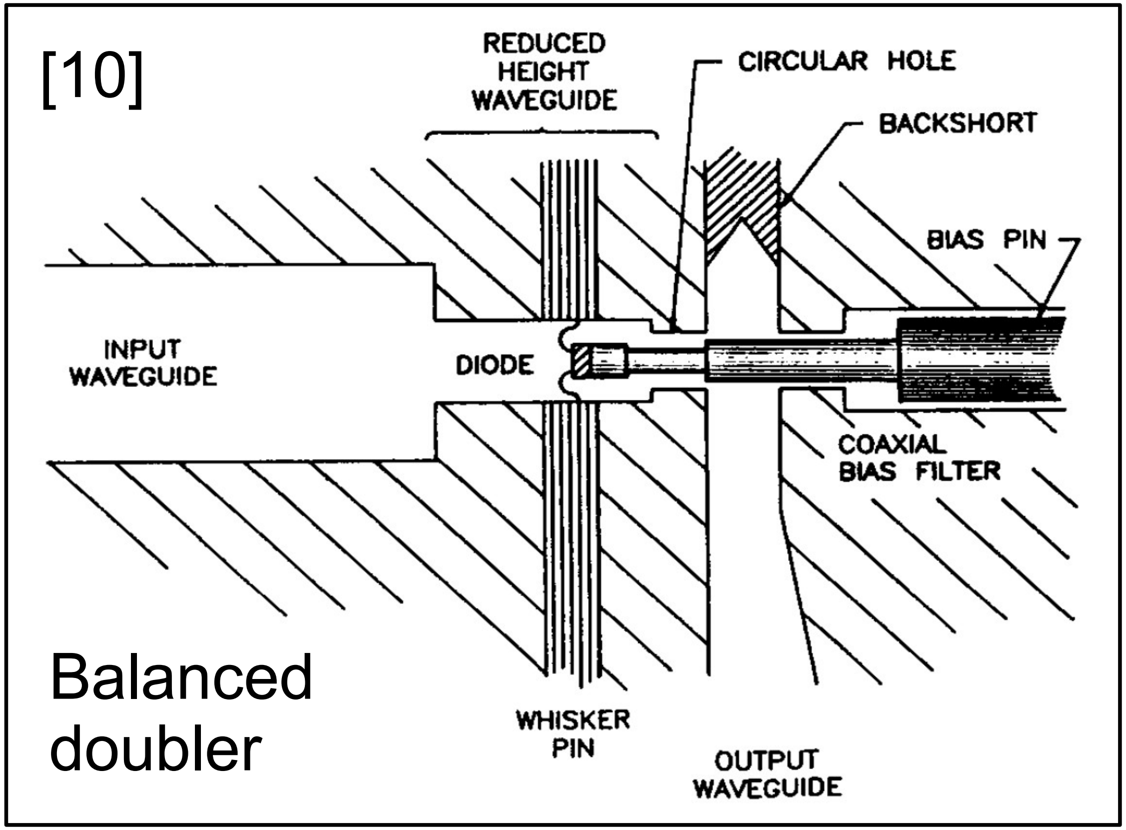
$C_J \approx 0.04pF$

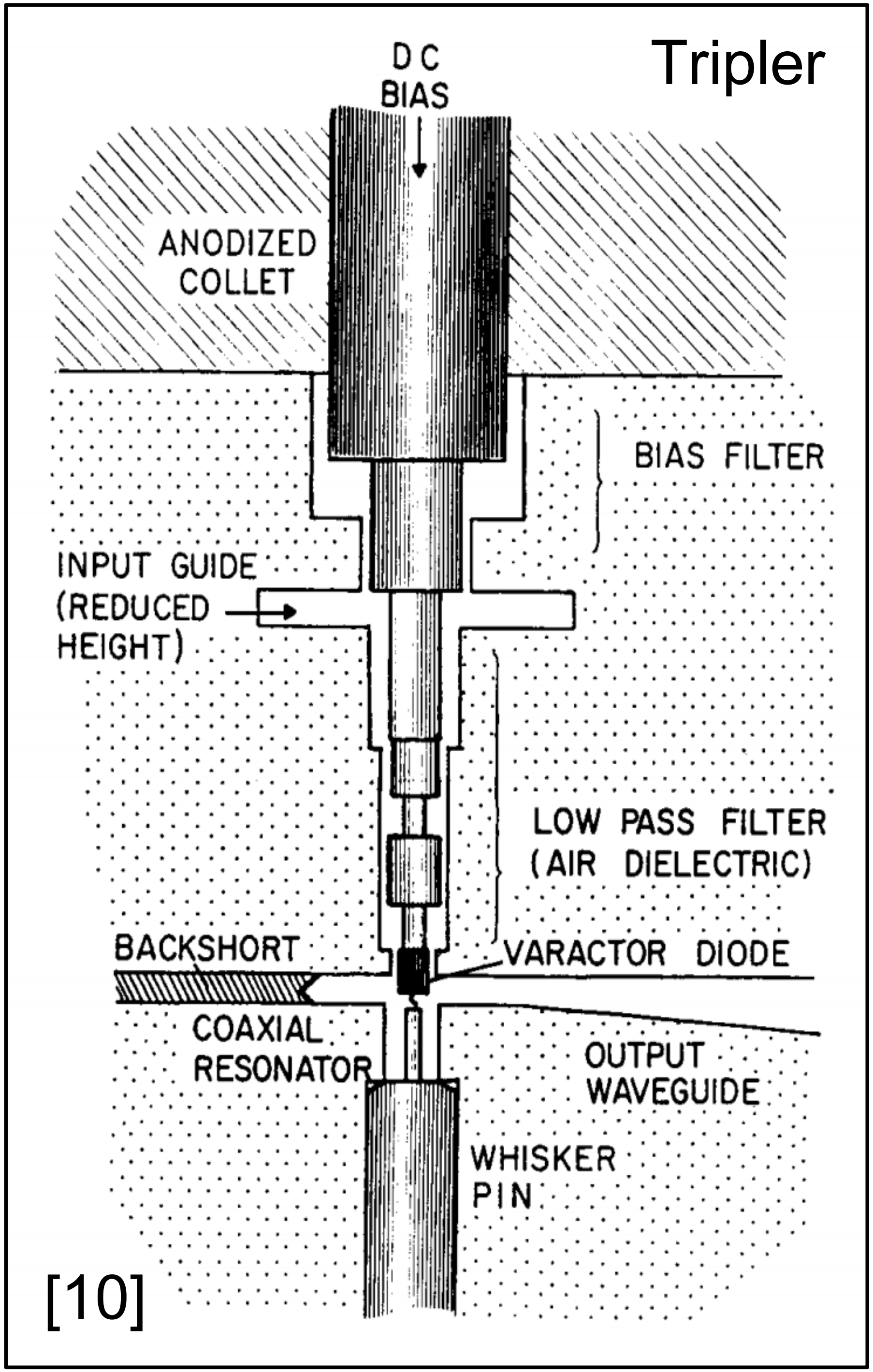
$R_S \approx 5\Omega$

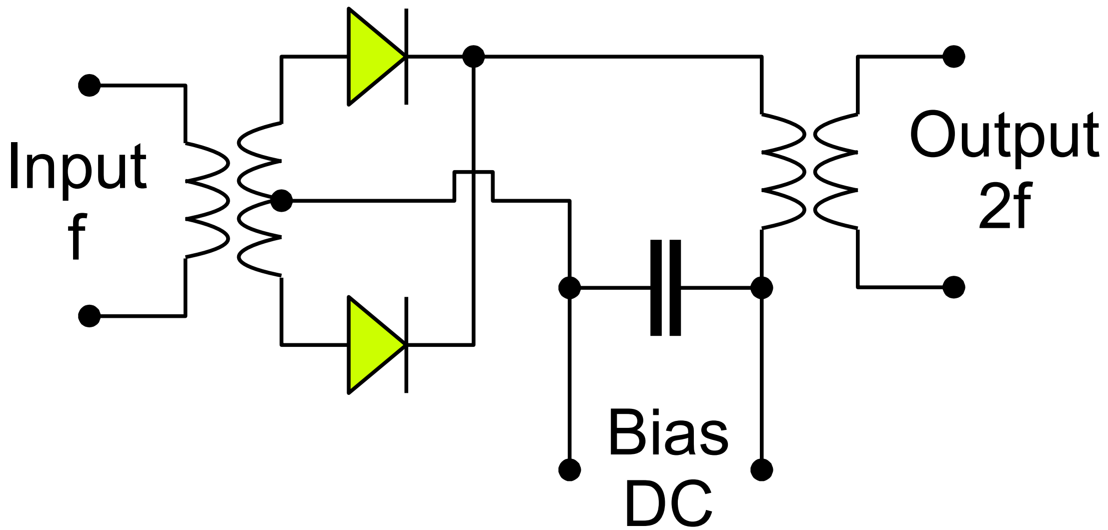
$\eta \approx 10\%$ (2f)

$\eta \approx 3\%$ (3f)

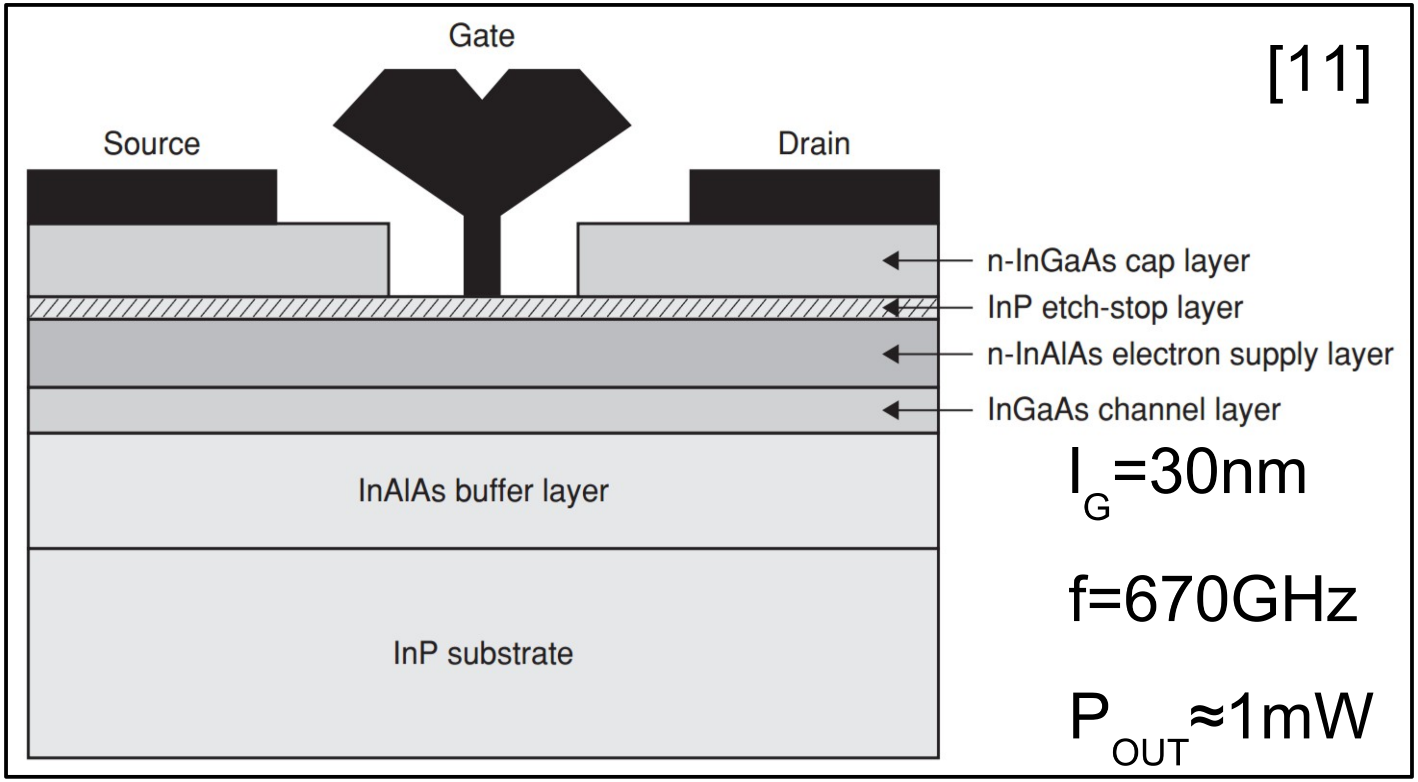
9 - GaAs flip-chip and beam-lead Schottky diodes

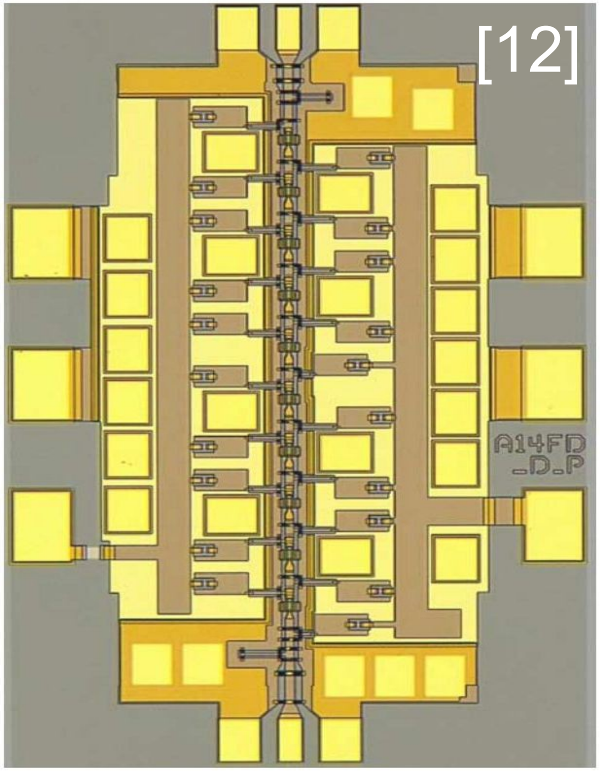


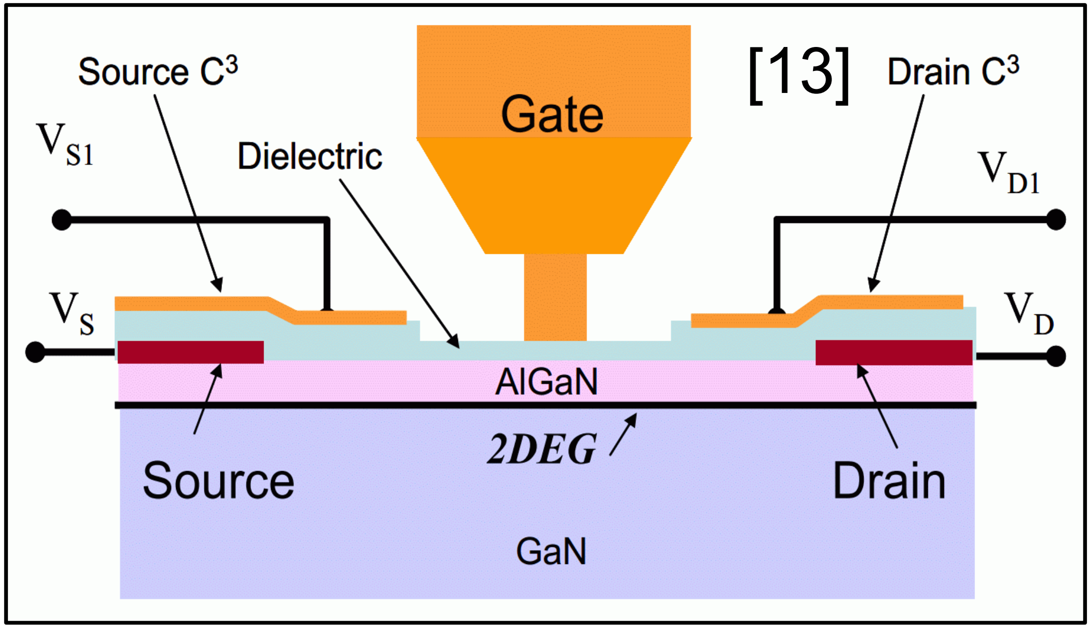


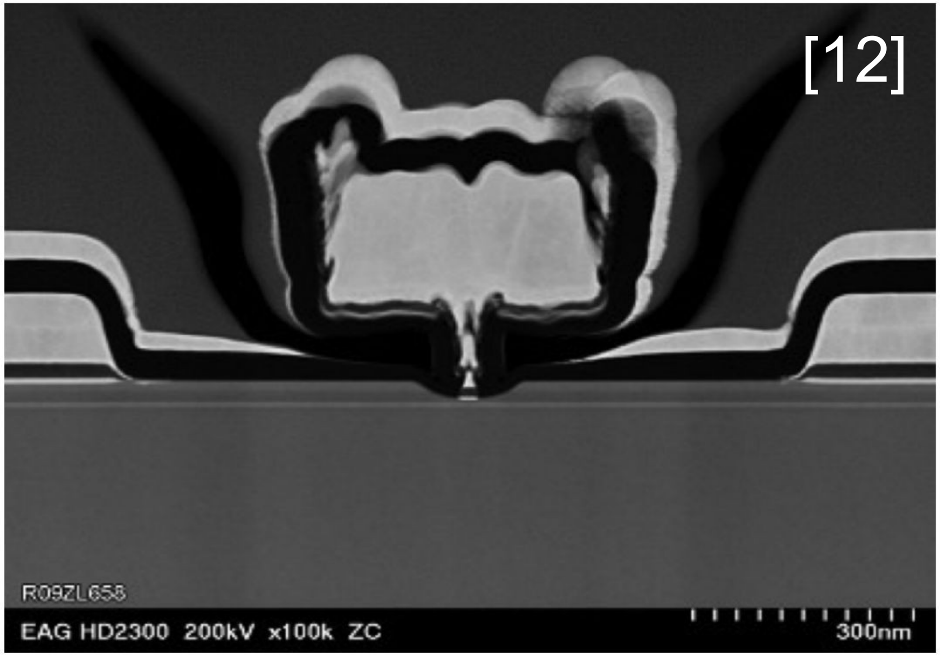


10 - Millimeter frequency doublers and triplers

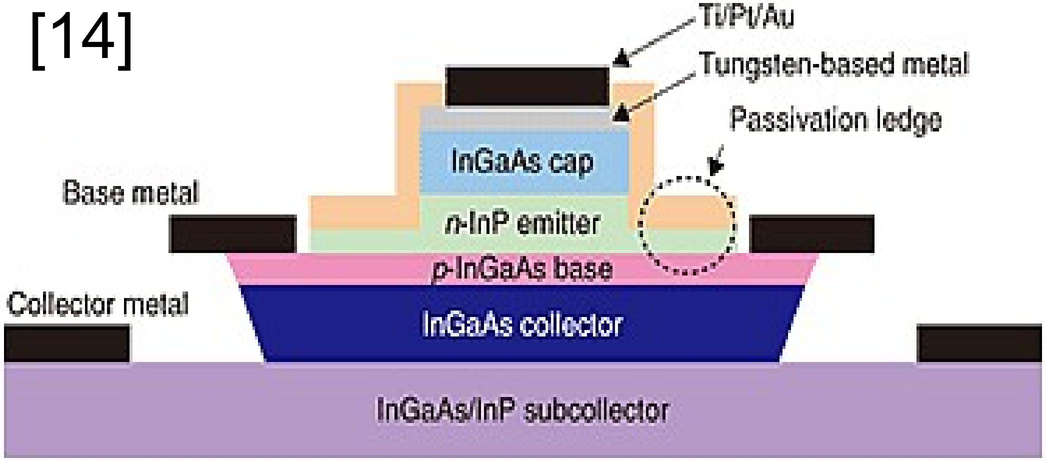




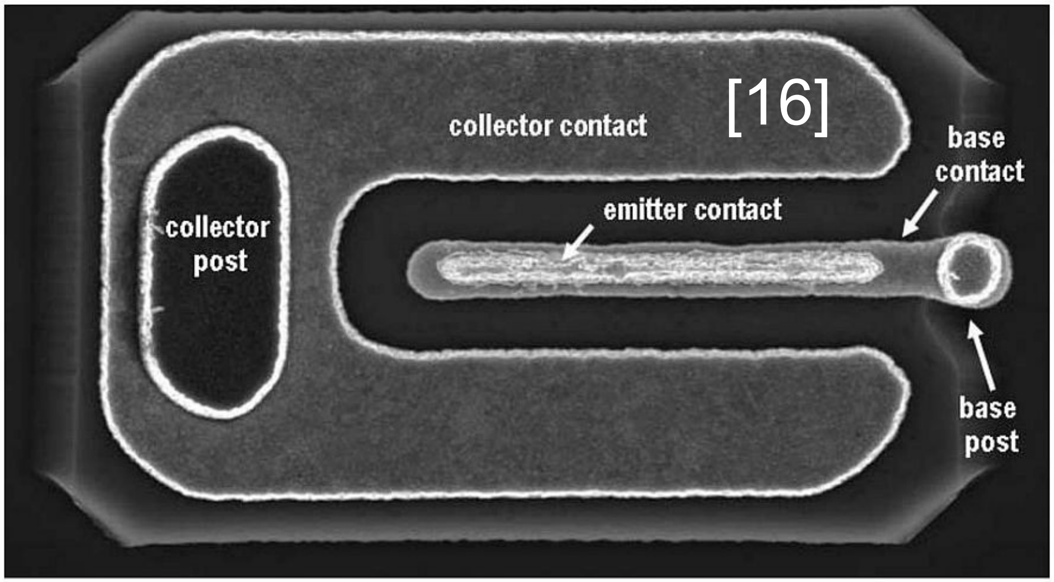


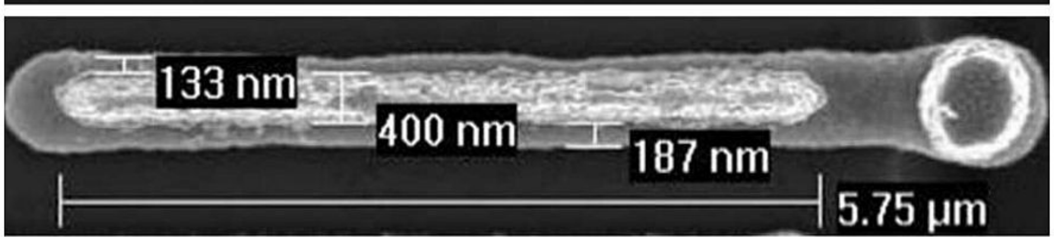


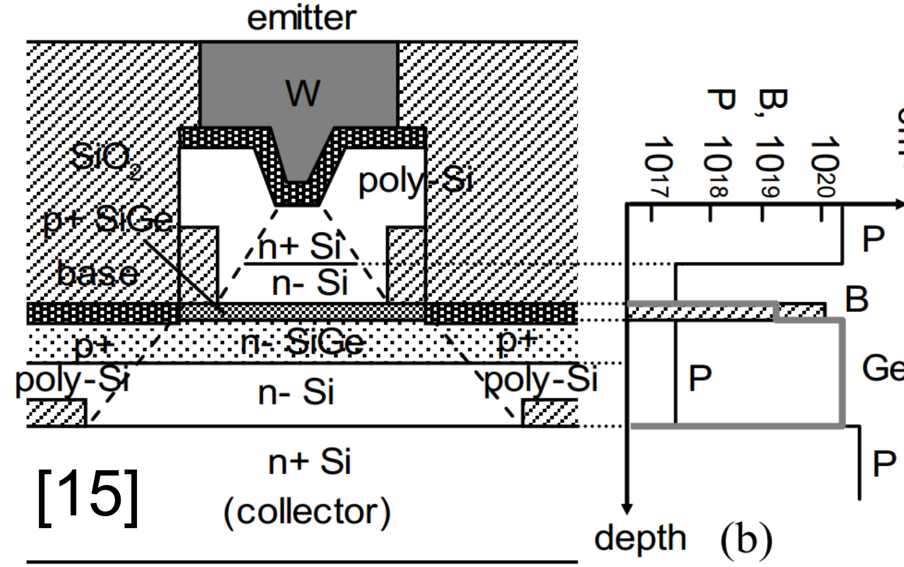
11 - InP / GaN High Electron Mobility Transistor (HEMT)

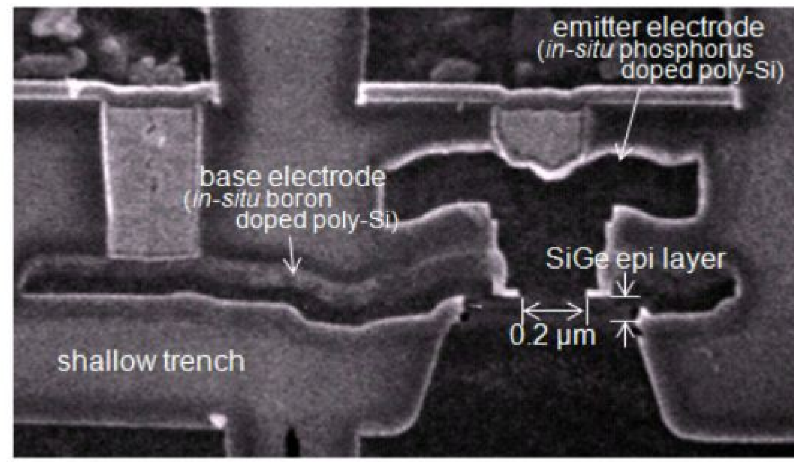


InP HBT

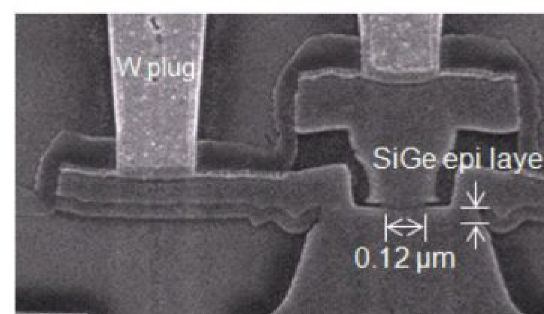






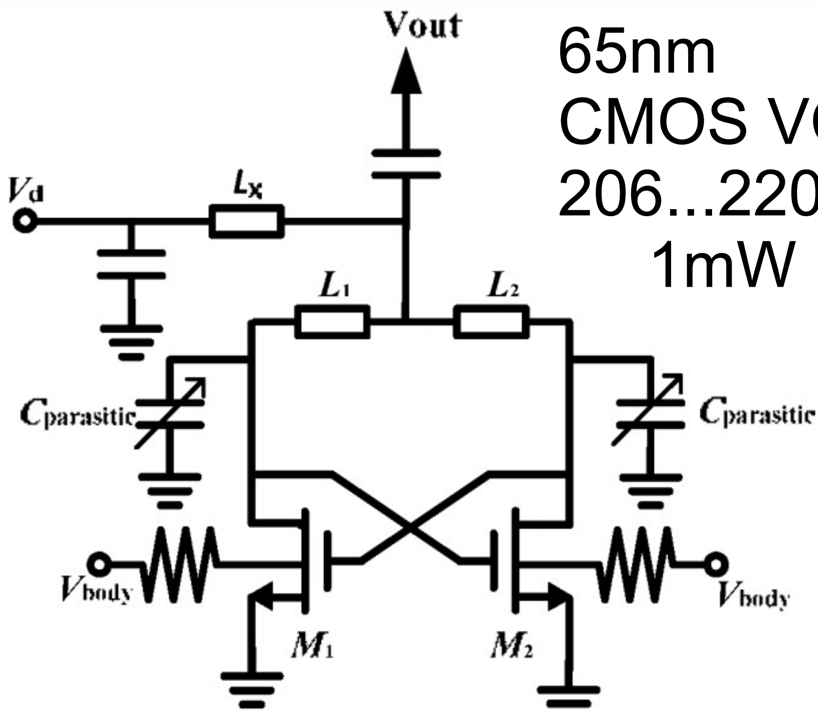


[17]

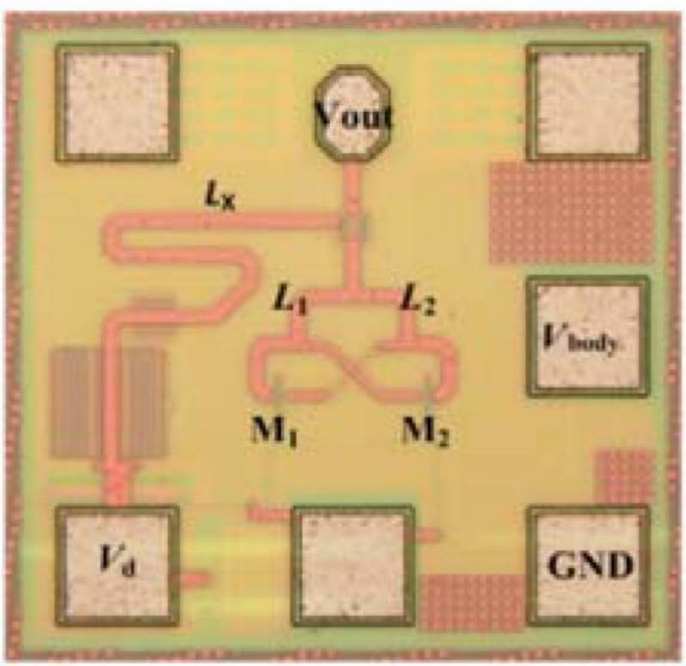


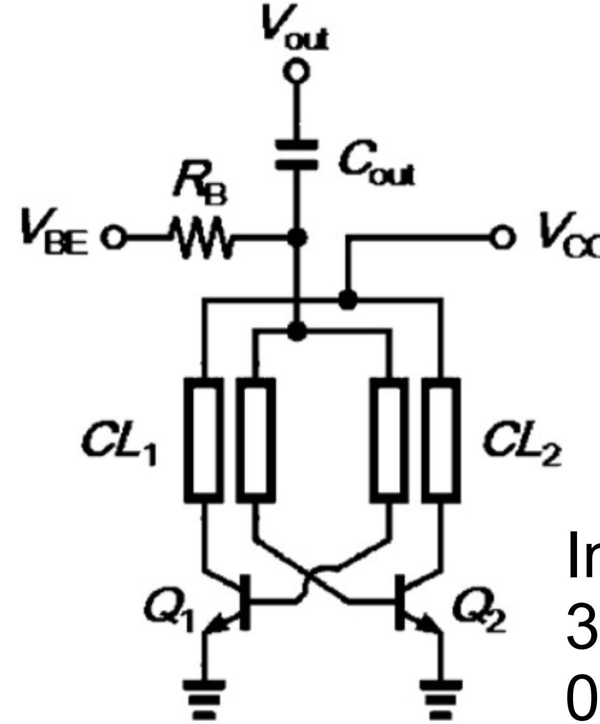
SiGe HBT

12 - InP / SiGe Heterostructure Bipolar Transistor (HBT)

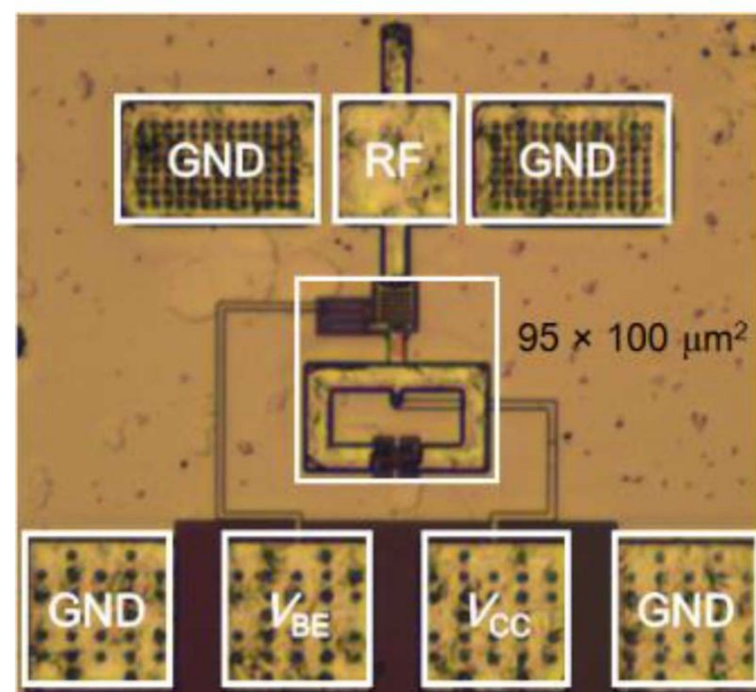


65nm
CMOS VCO
206...220GHz
1mW [18]



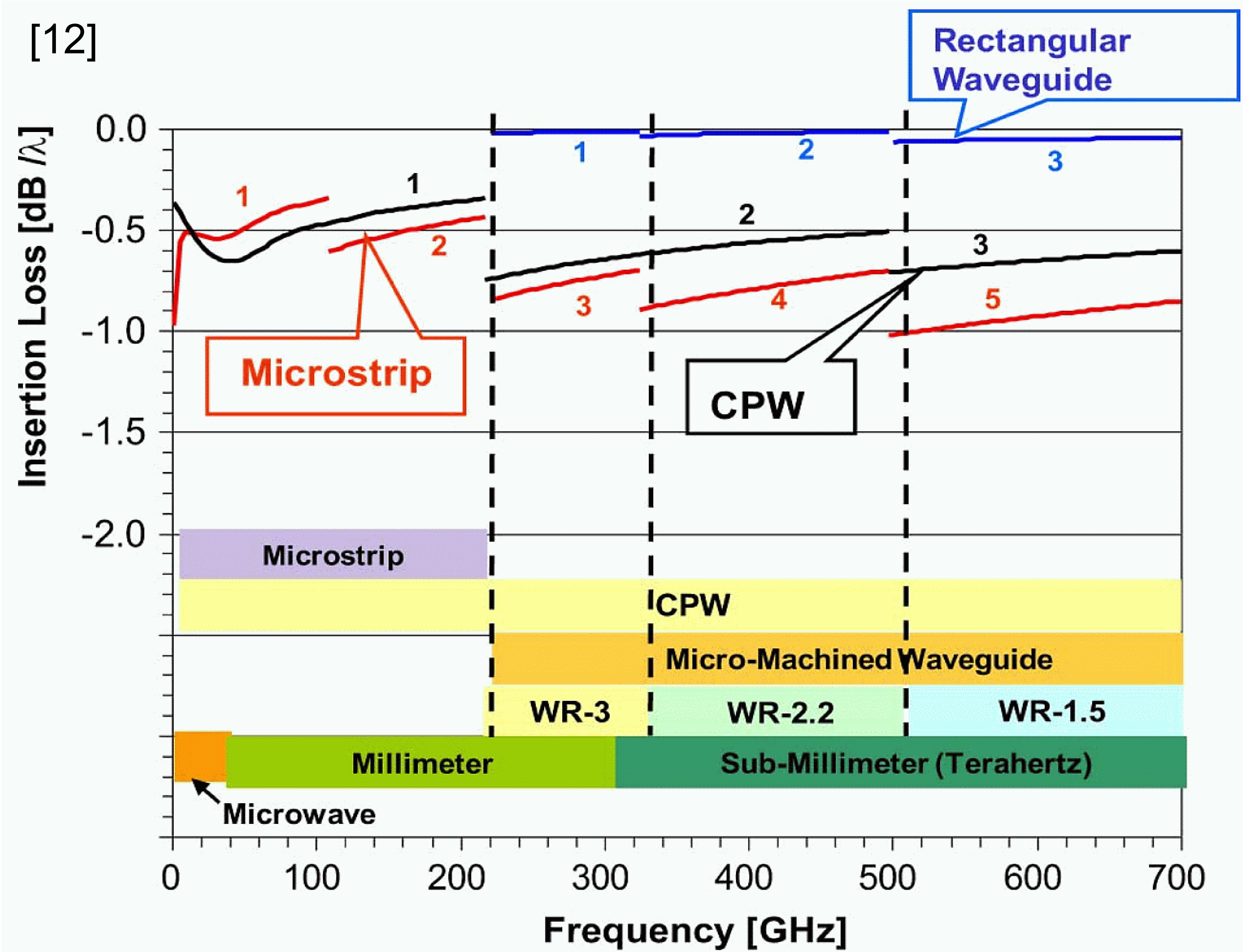


0.25µm
InP HBT VCO
310...340GHz
0.2mW [19]

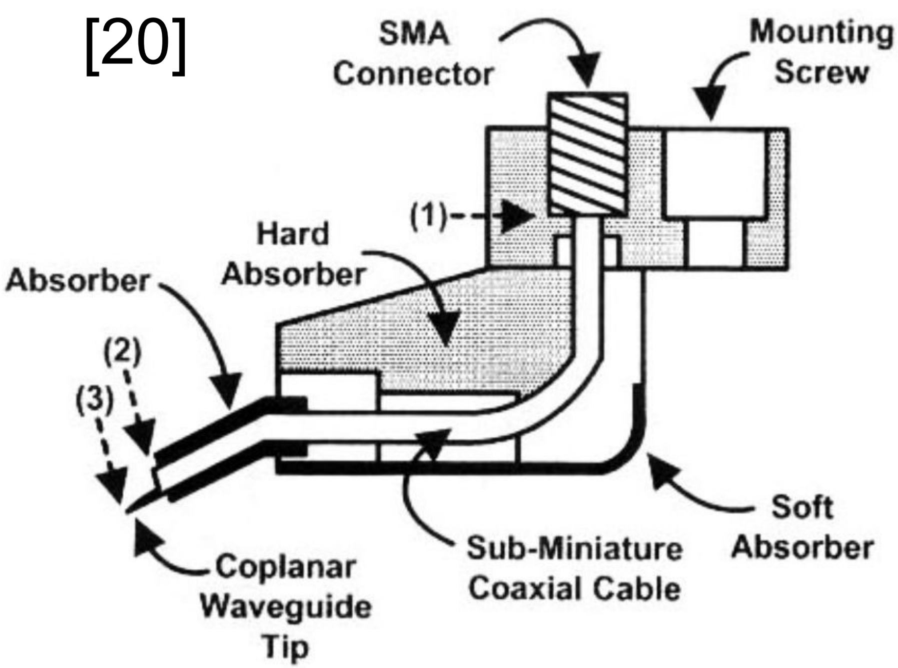


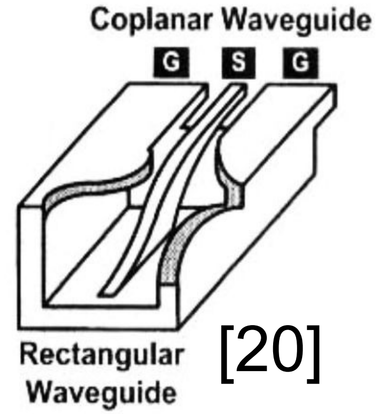
13 - Push-push oscillator / doubler

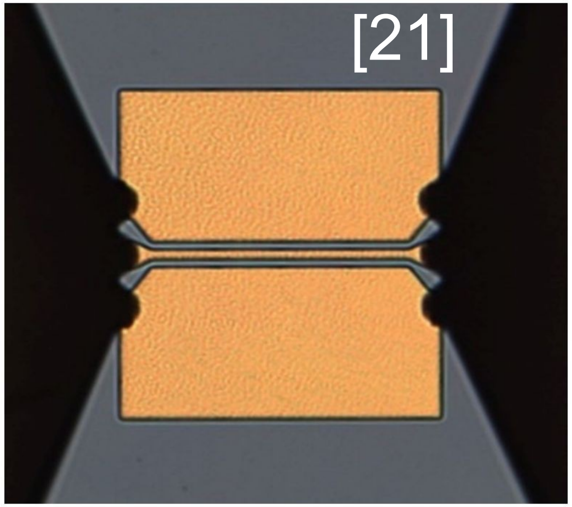
[12]

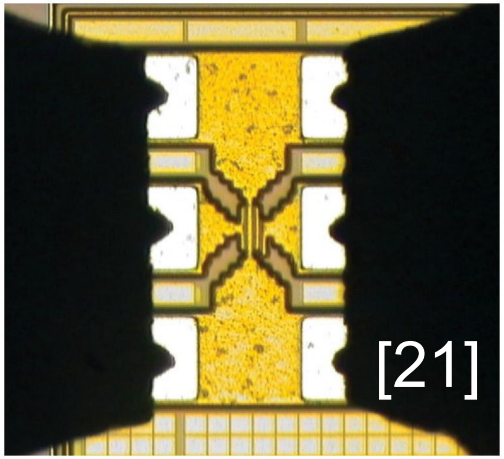


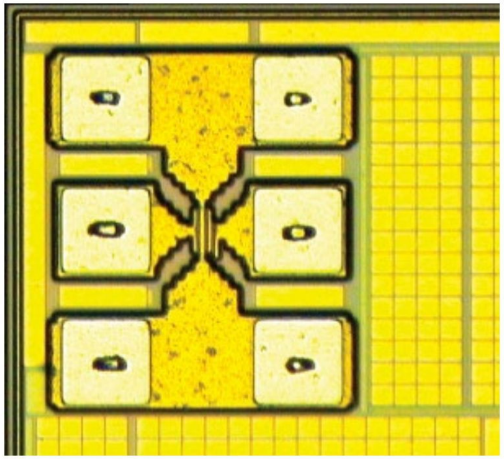
14 - Transmission-line losses in the mm / THz range

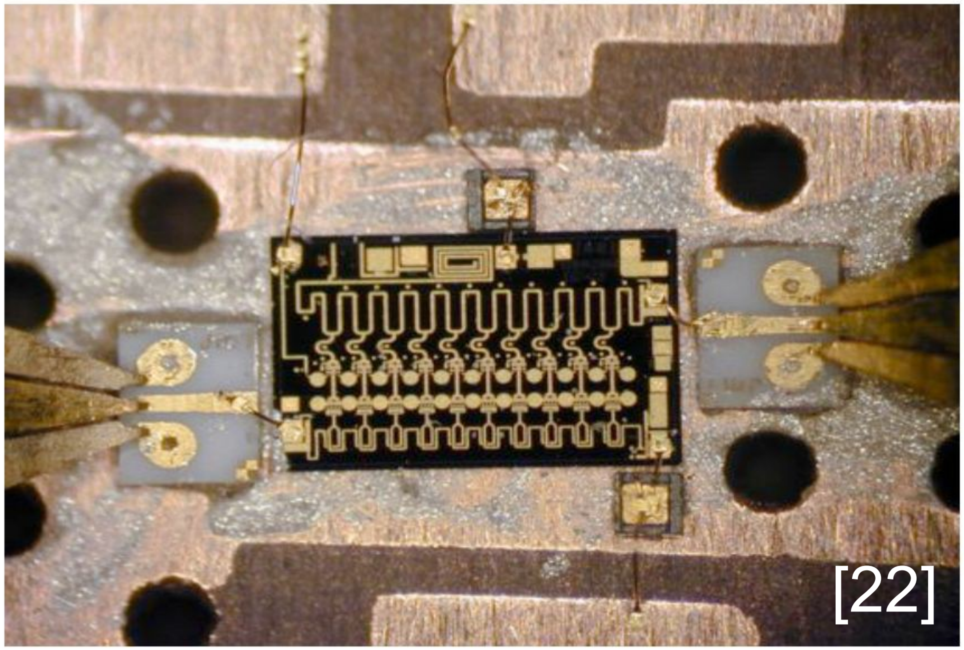


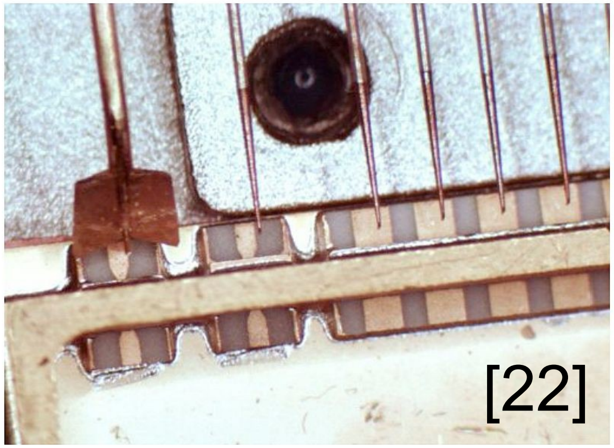




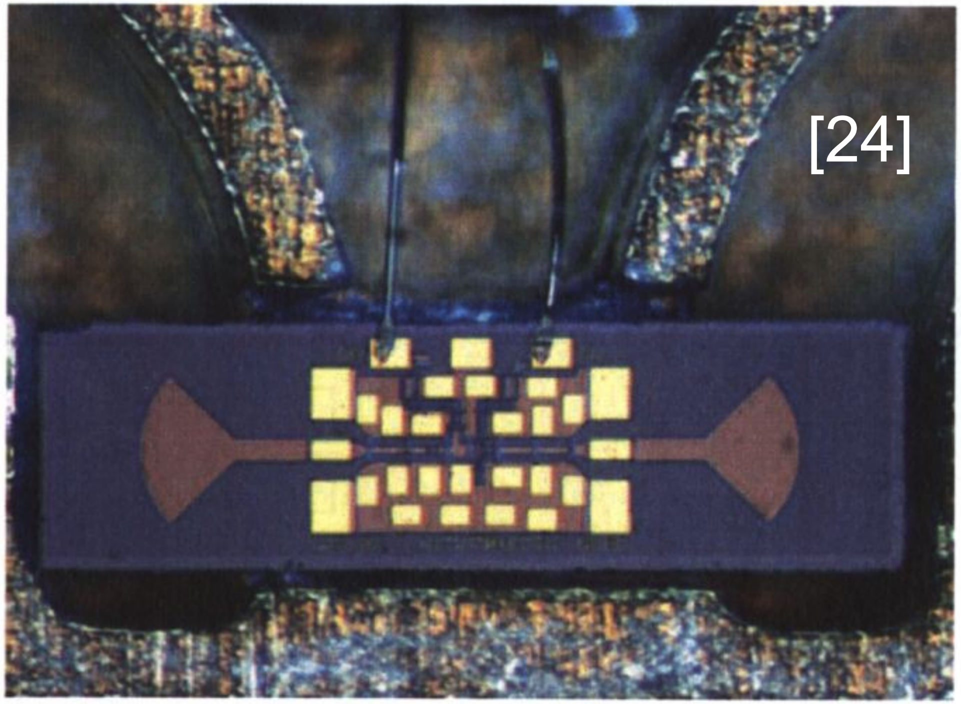


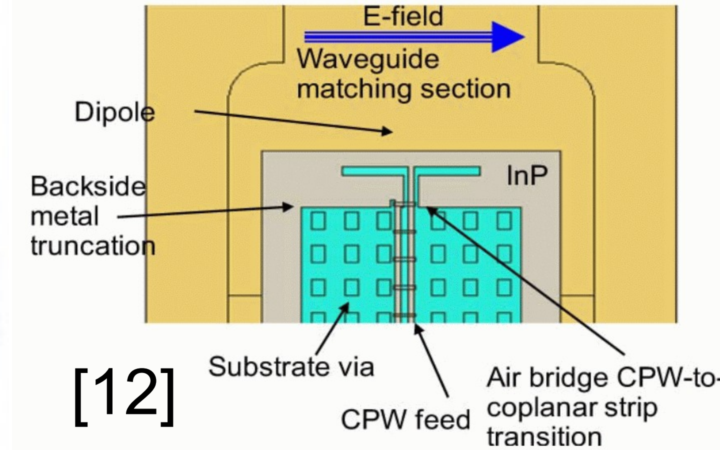


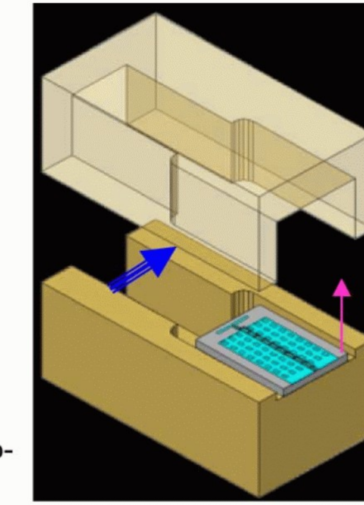


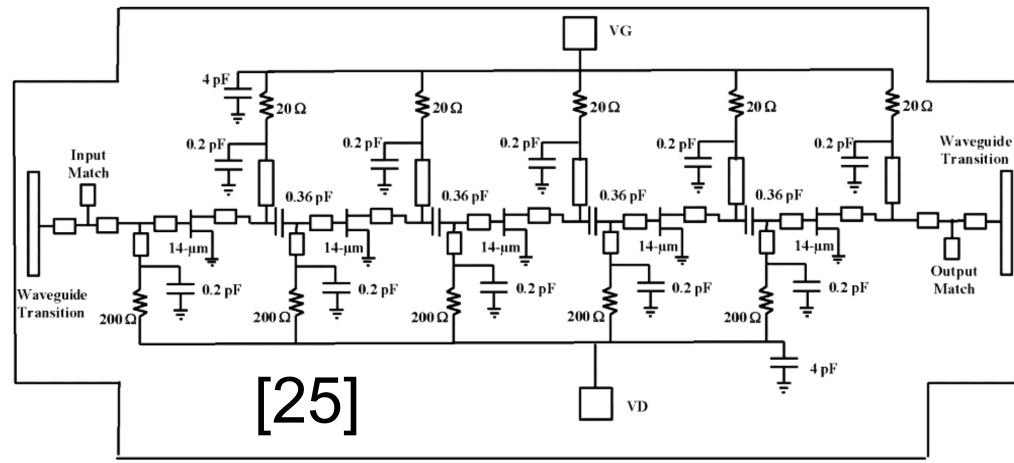


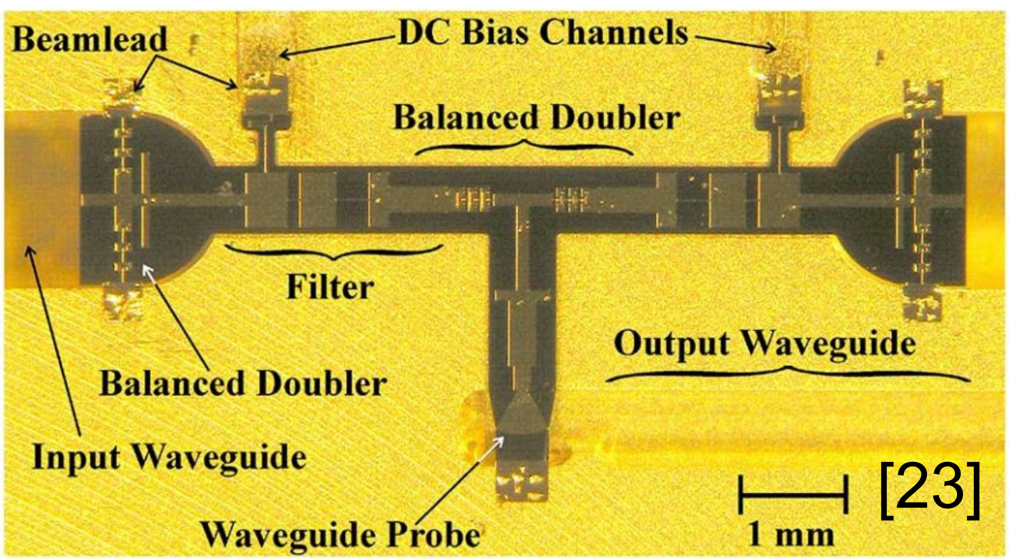
15 - Coplanar-waveguide (CPW) GSG probes

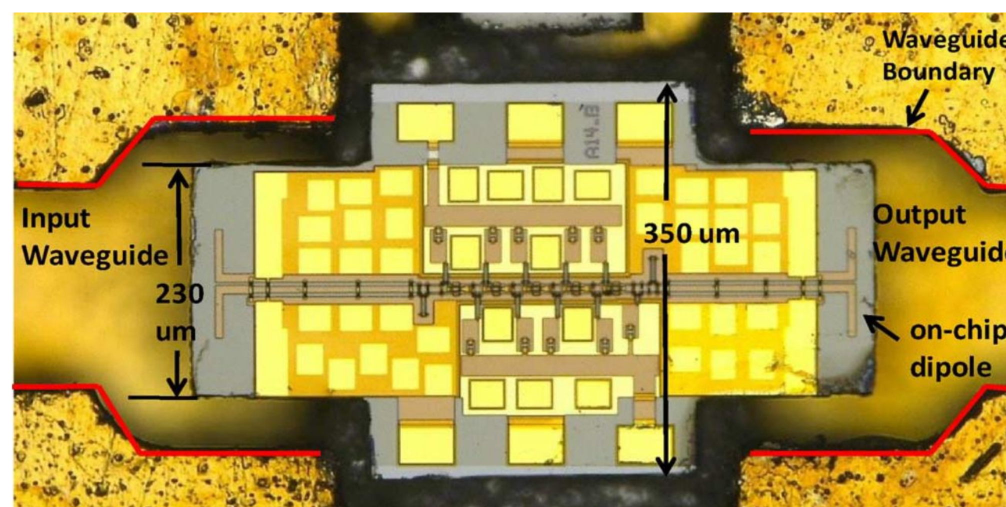




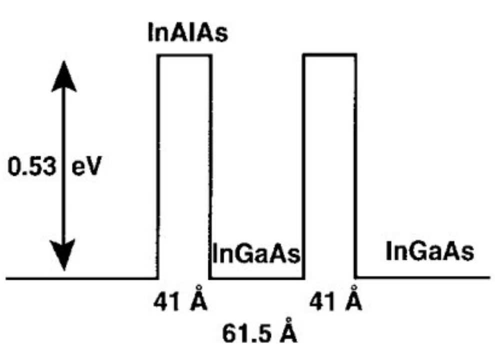




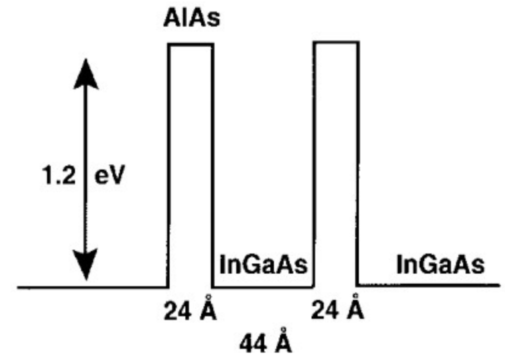


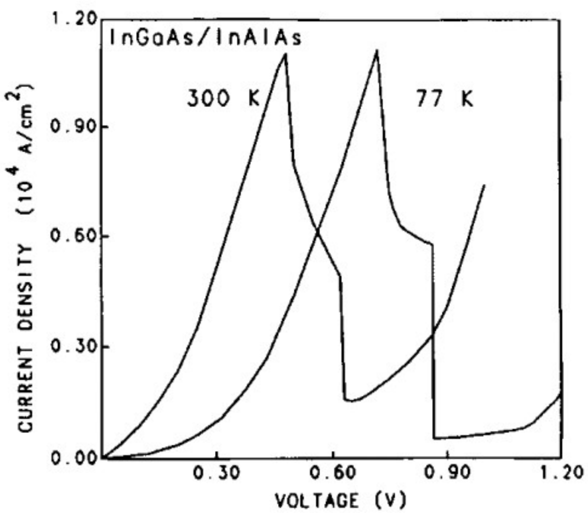


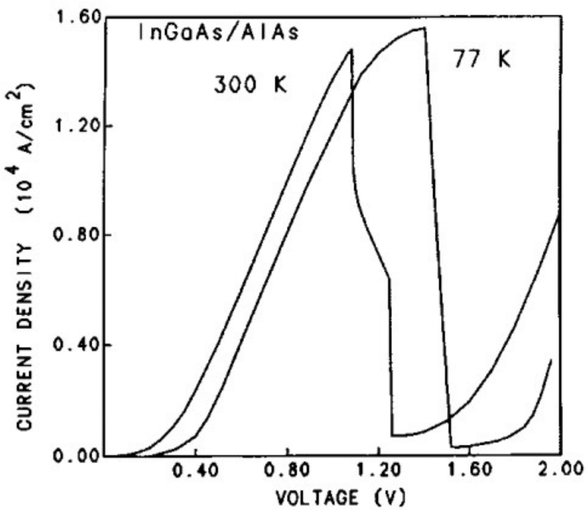
16 - Chip-to-waveguide transitions



[26]

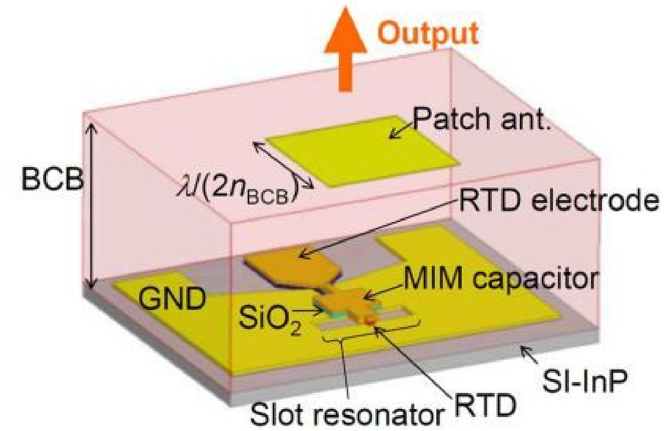


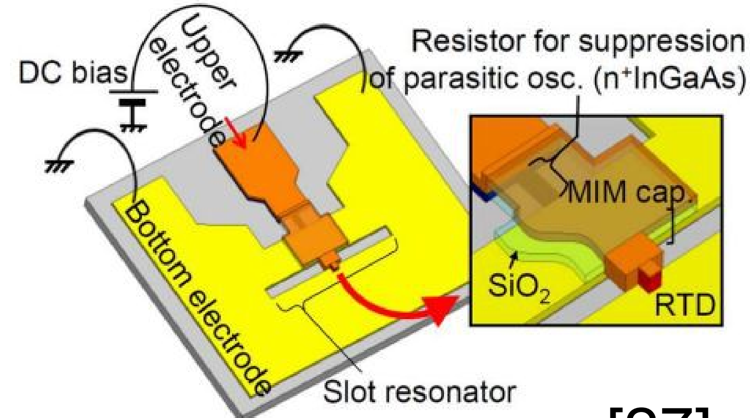




PVR ~ 6 @ 300 K
16 @ 77 K

PVR ~ 23 @ 300 K
53 @ 77 K





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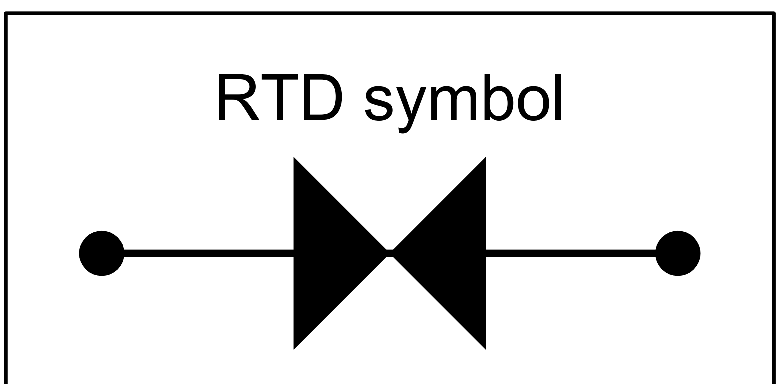
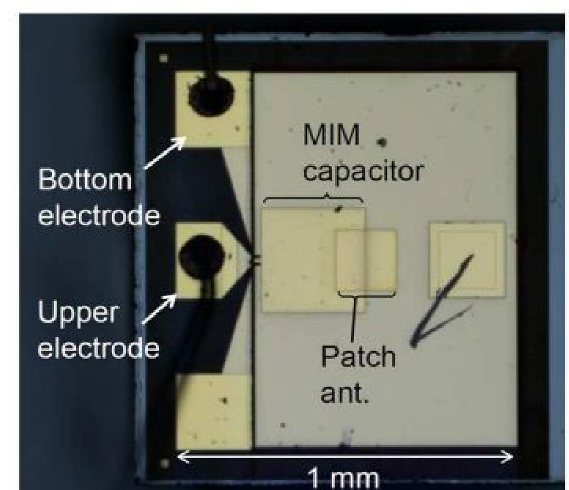
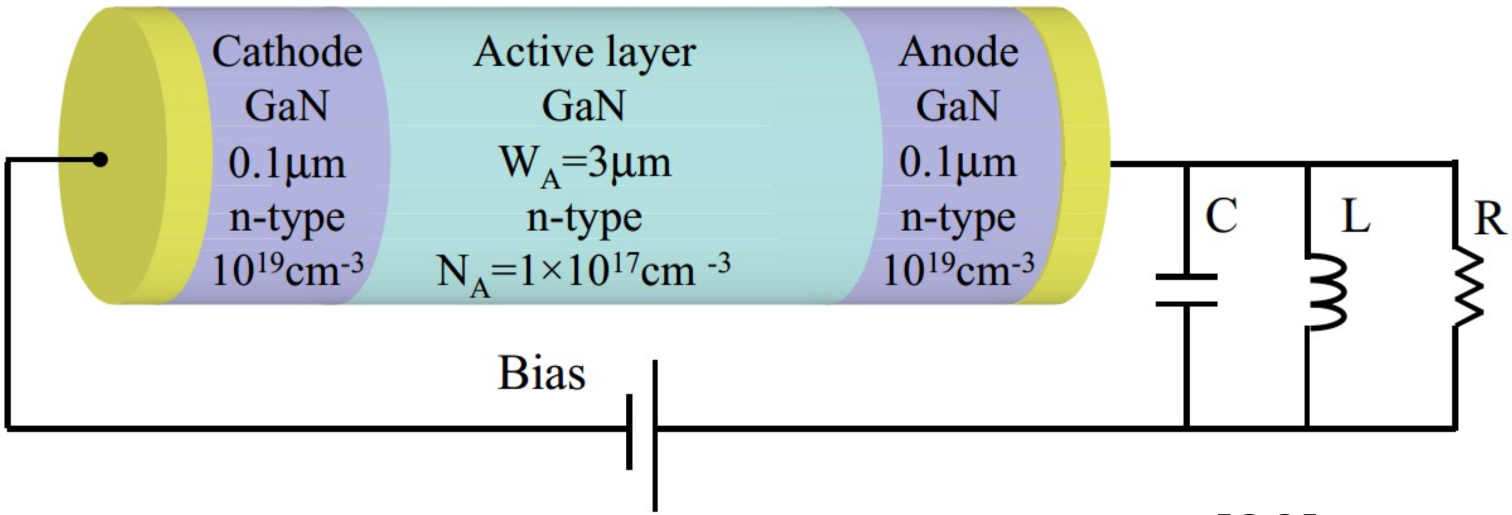


f≈510GHz

P≈40μW



17 - Resonant tunnel diode (RTD)



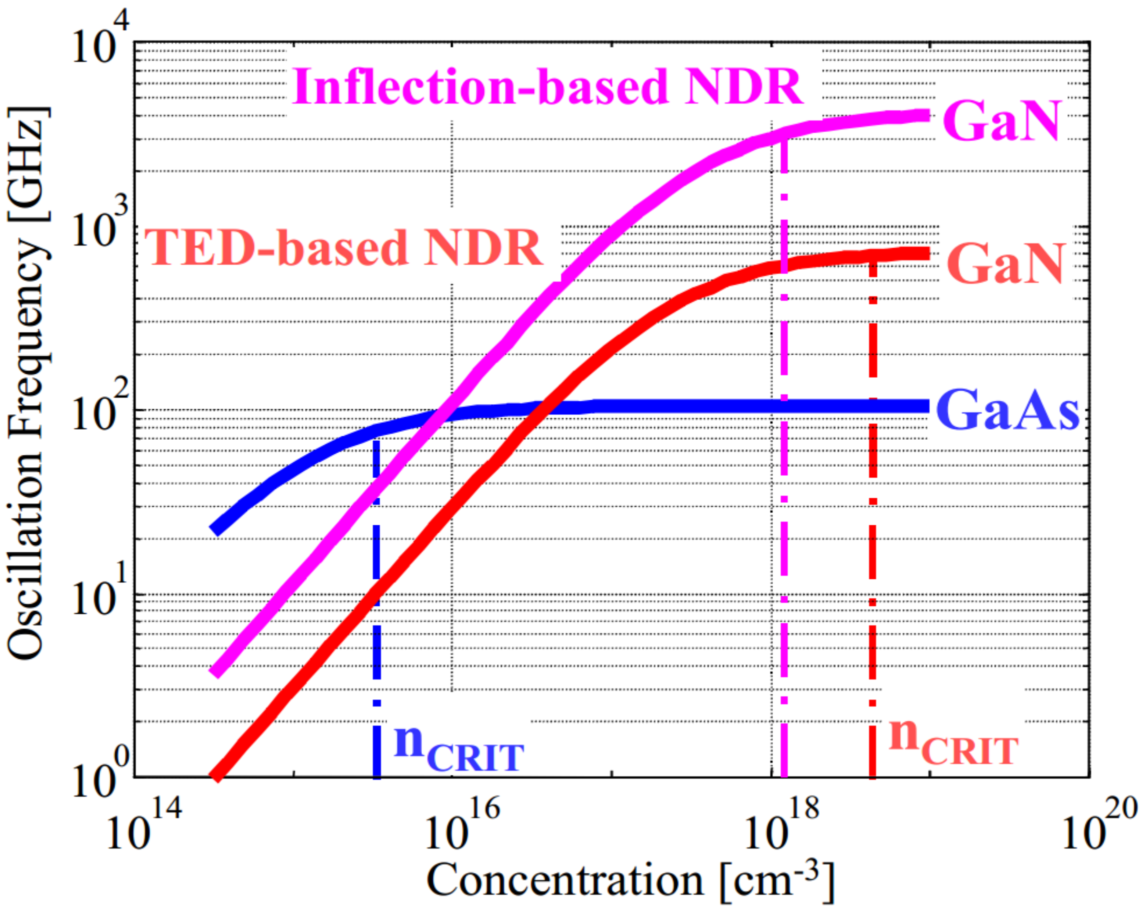
$f_{GaAs} \approx 100GHz$

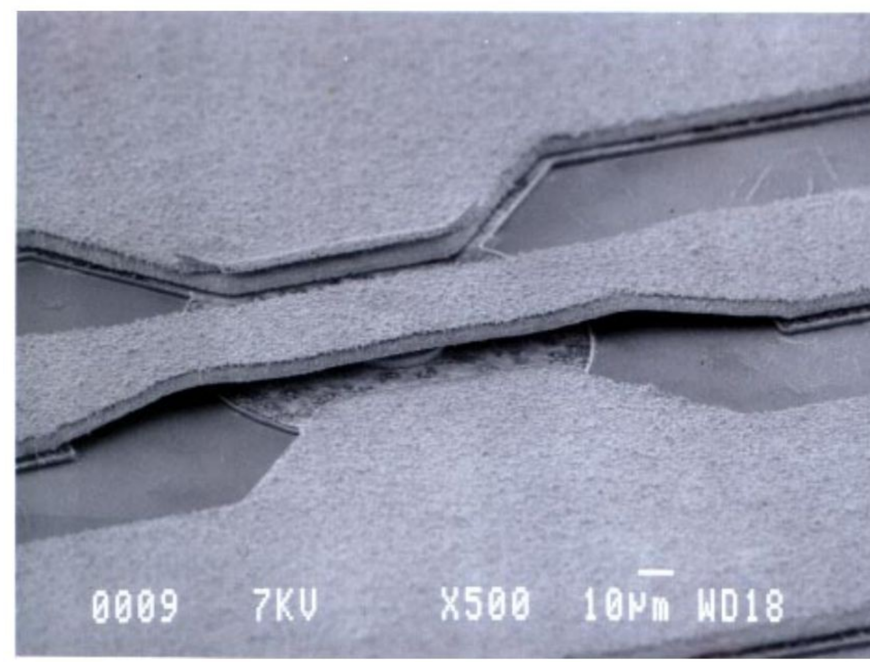
$f_{InP} \approx 250GHz$

$f_{GaN} \approx 3THz$

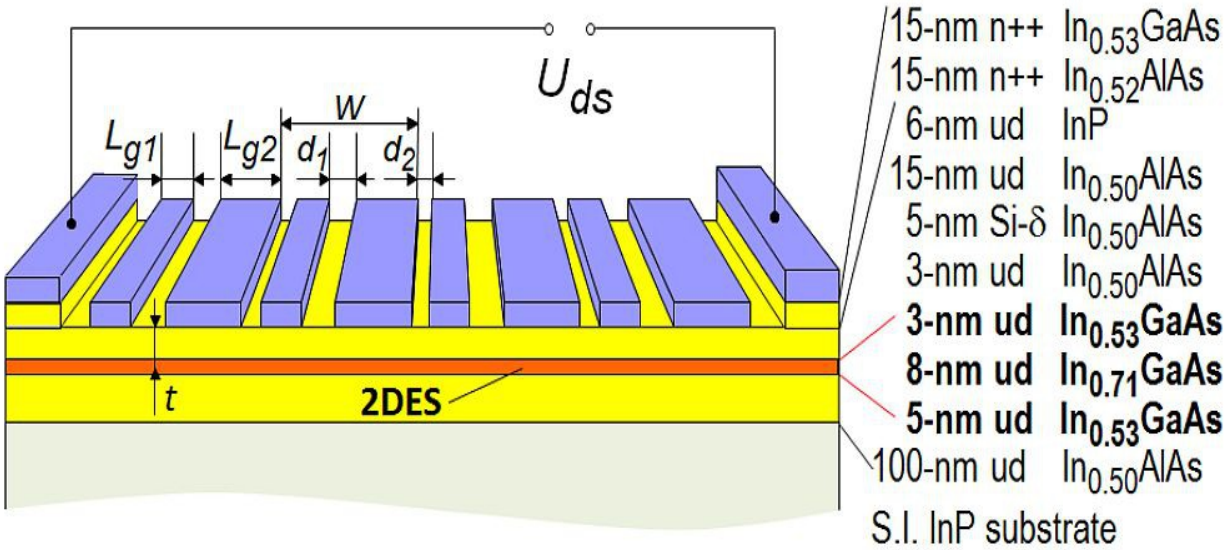
P≈100mW

[28]

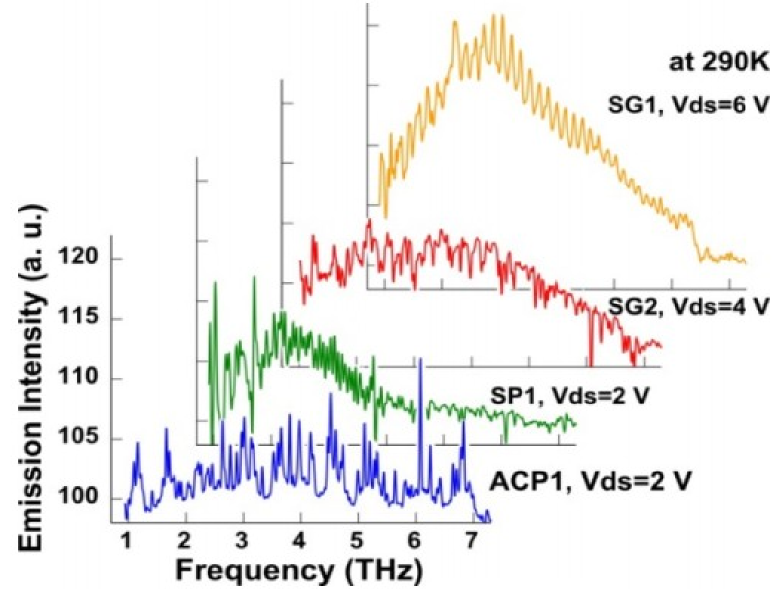


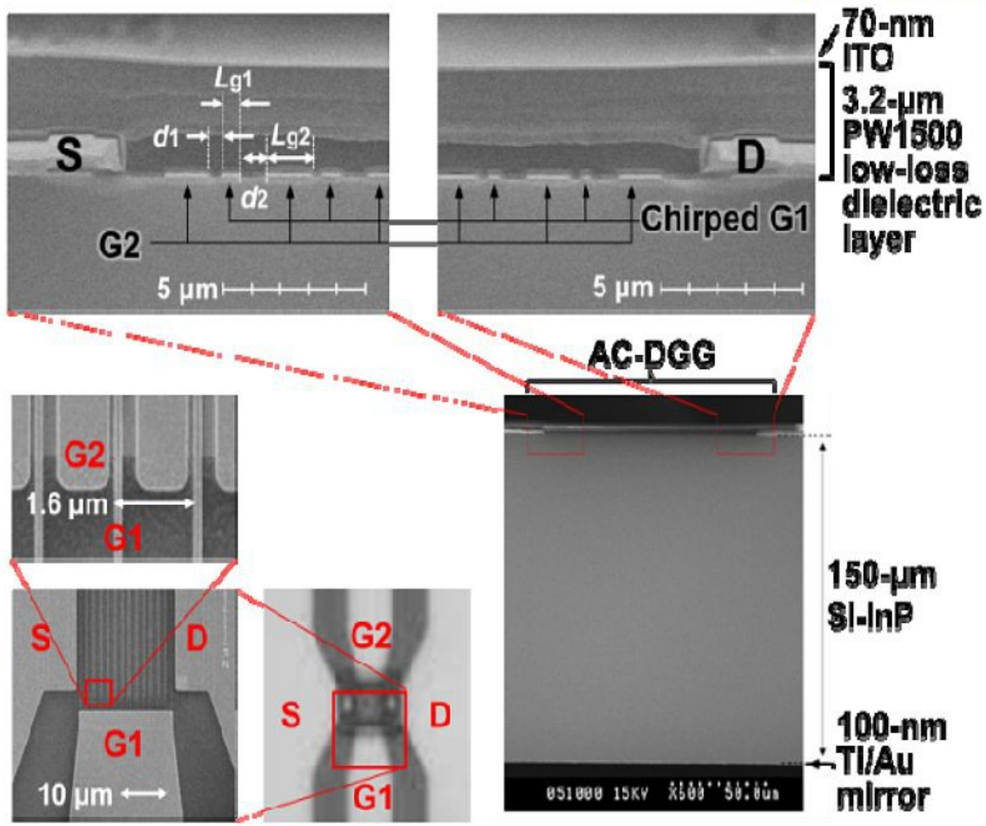


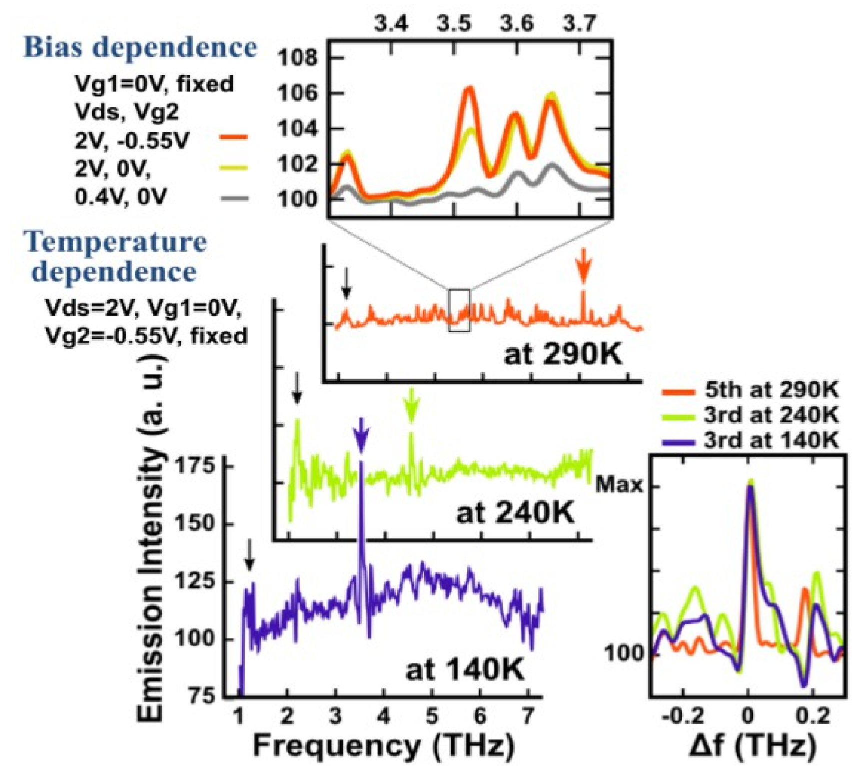
18 - Negative-differential-resistance (NDR) diodes (Gunn, TED)



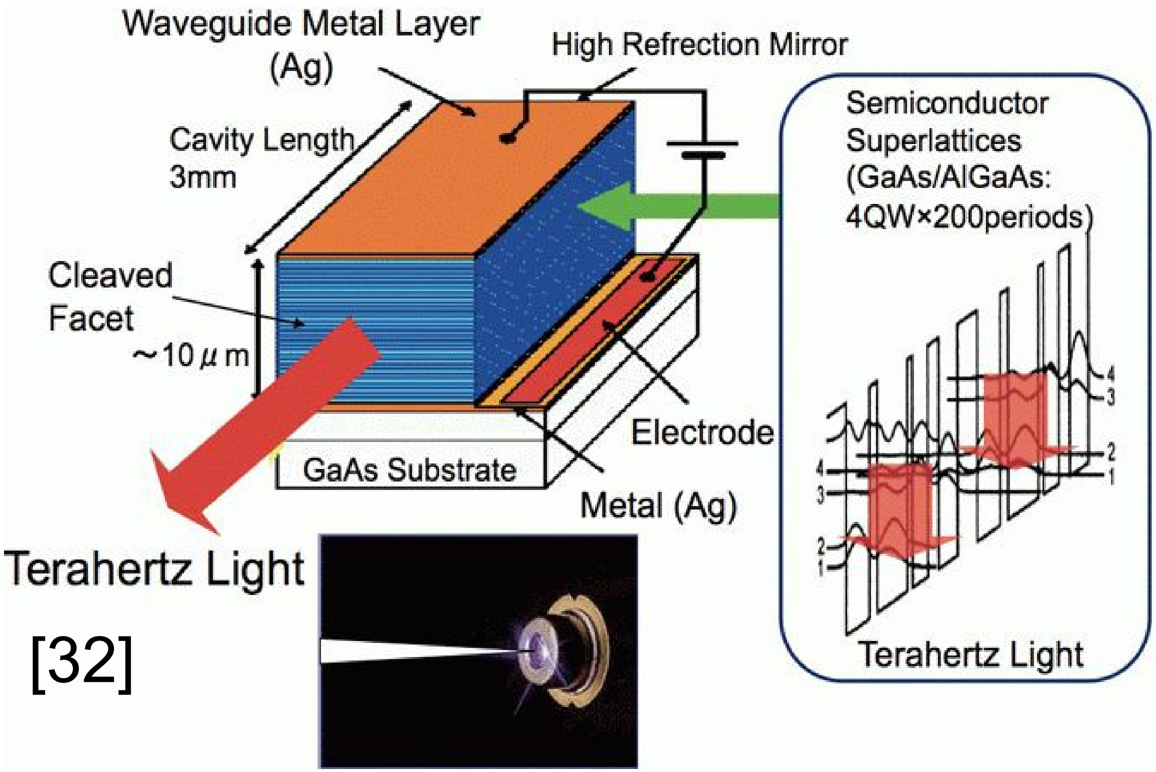
[29] P≈100nW...1μW



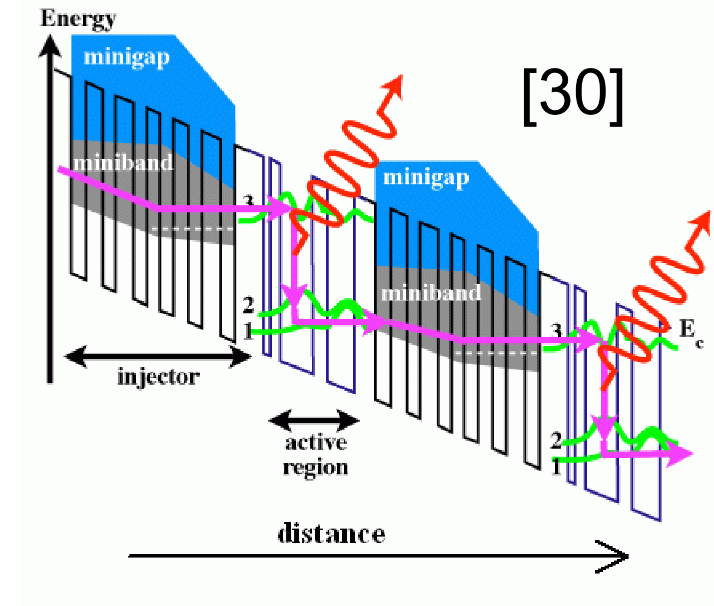




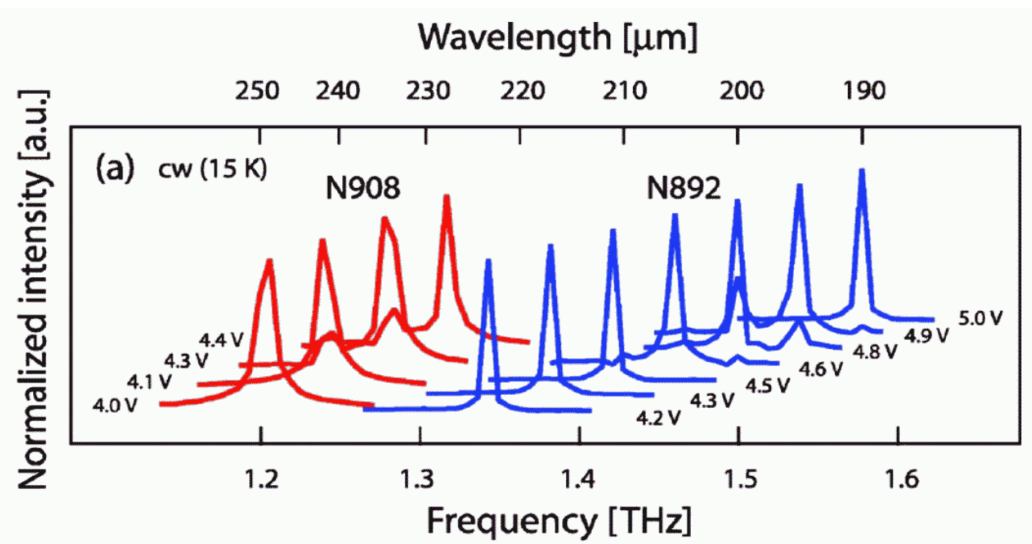
19 - Plasmonic mm / THz sources

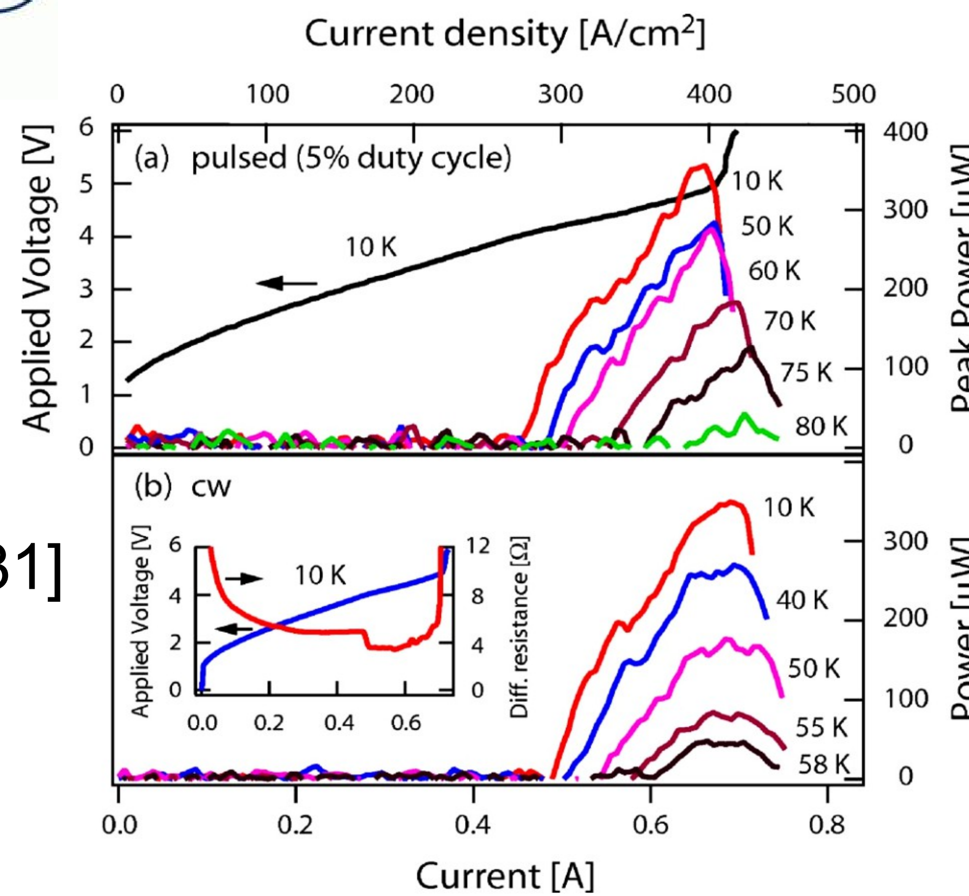


[32]



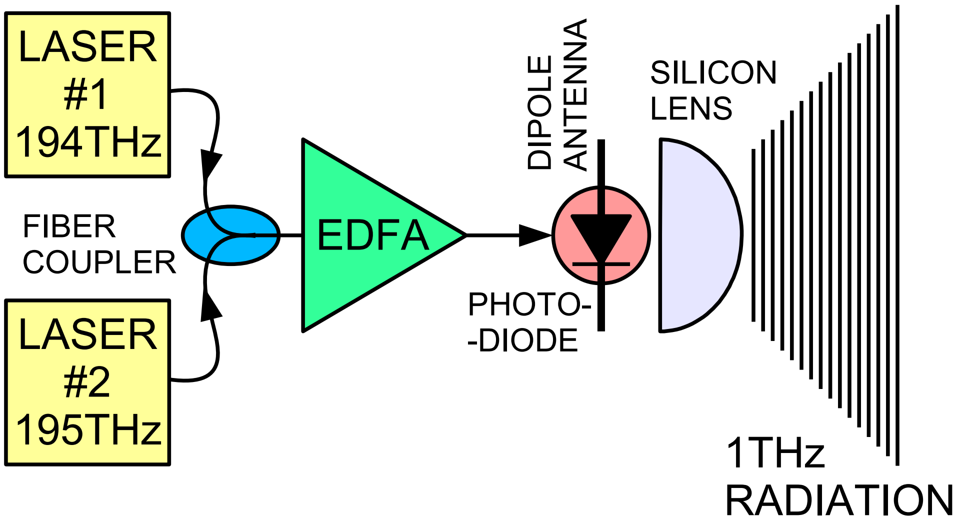
[30]

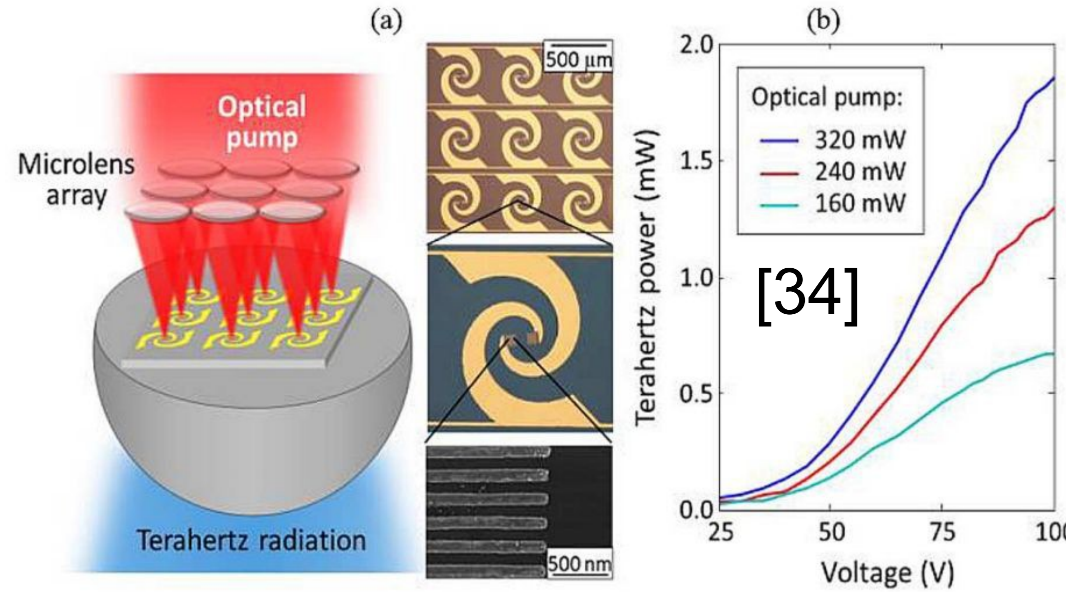


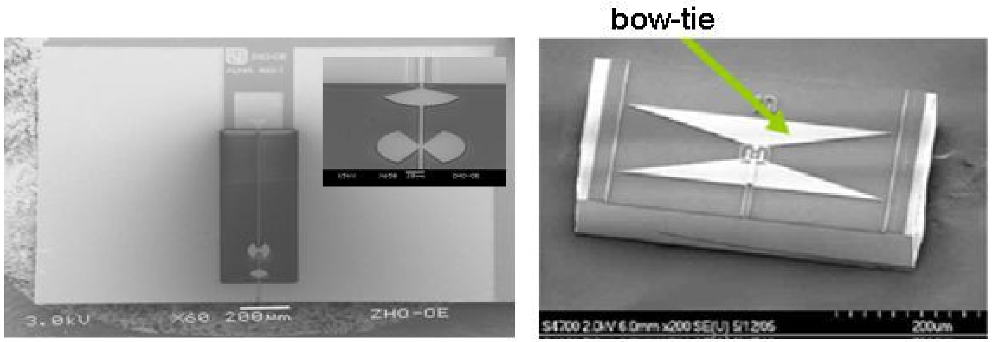


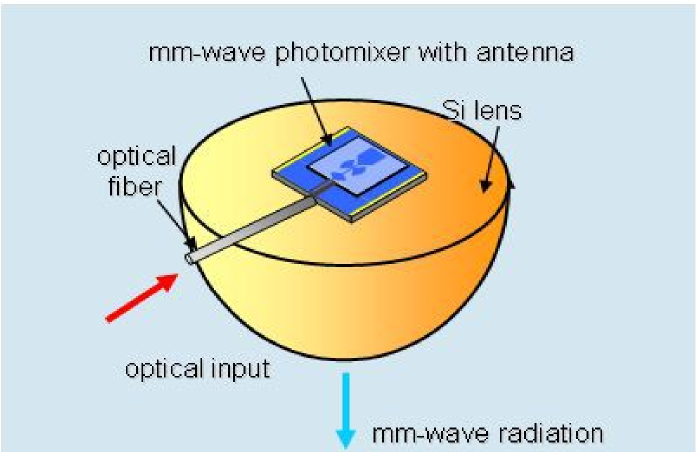
[31]

20 - Quantum-cascade laser

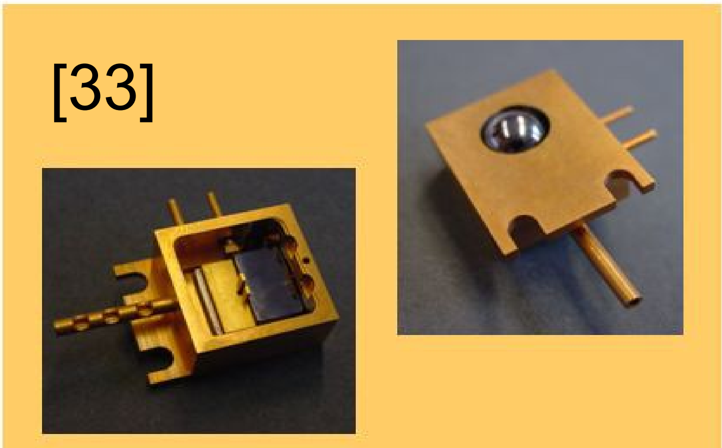








photonic 30-300GHz transmitter chip



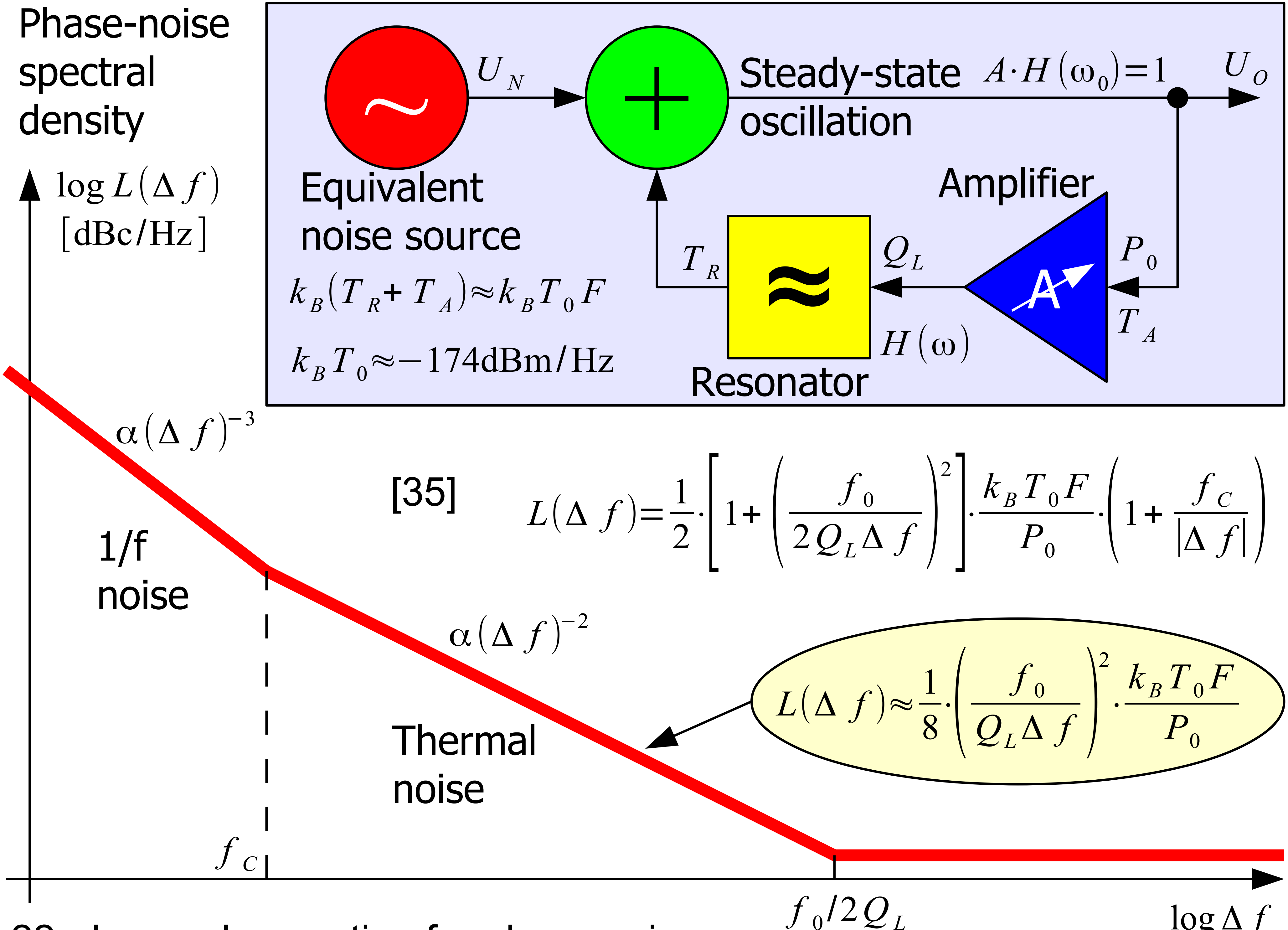
packaged photonic transmitter

WIDE FREQUENCY RANGE

LOW POWER P≈10µW...1mW

LASER PHASE NOISE?

21 - Electro-optical mm / THz sources

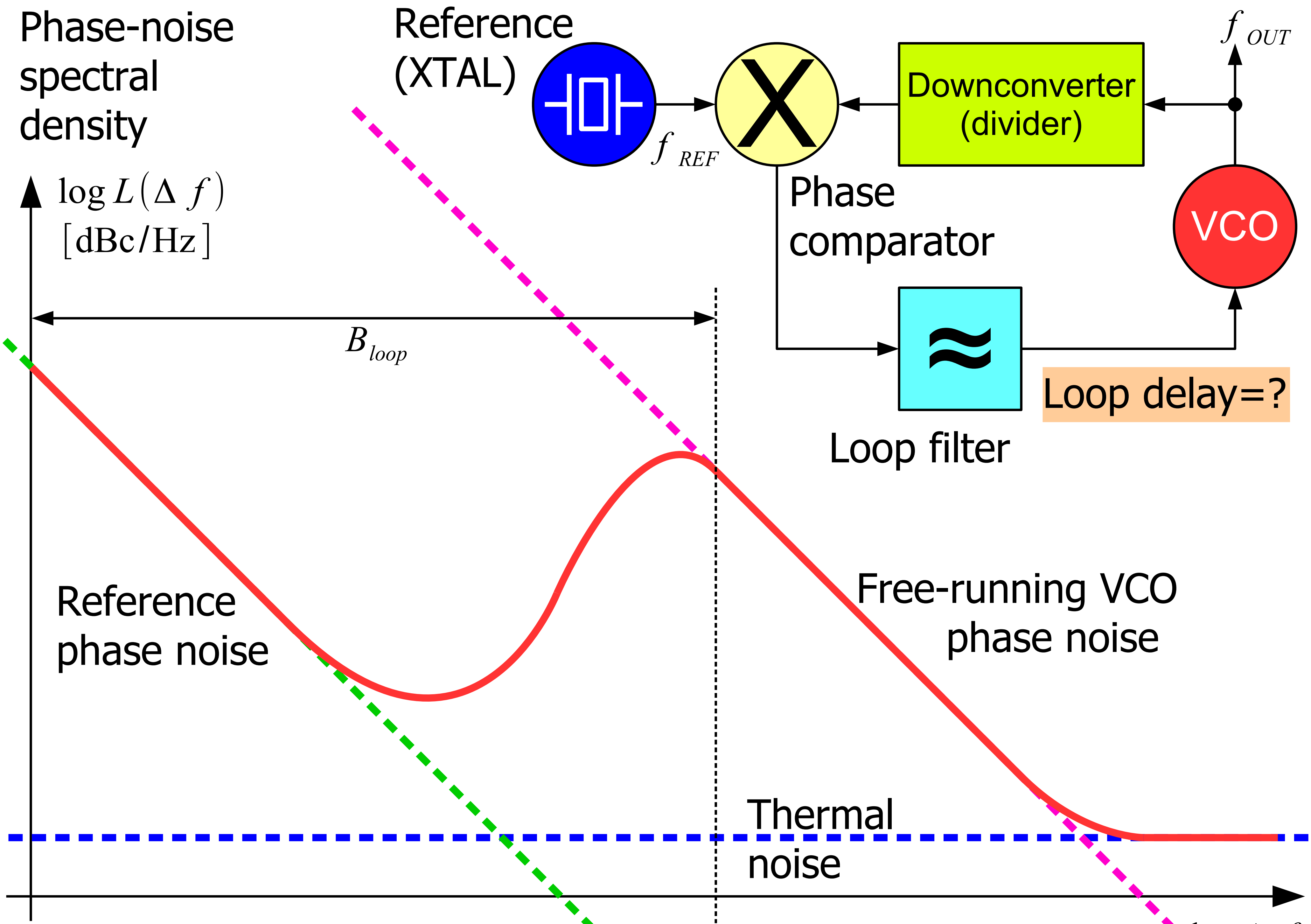


22 - Leeson's equation for phase noise

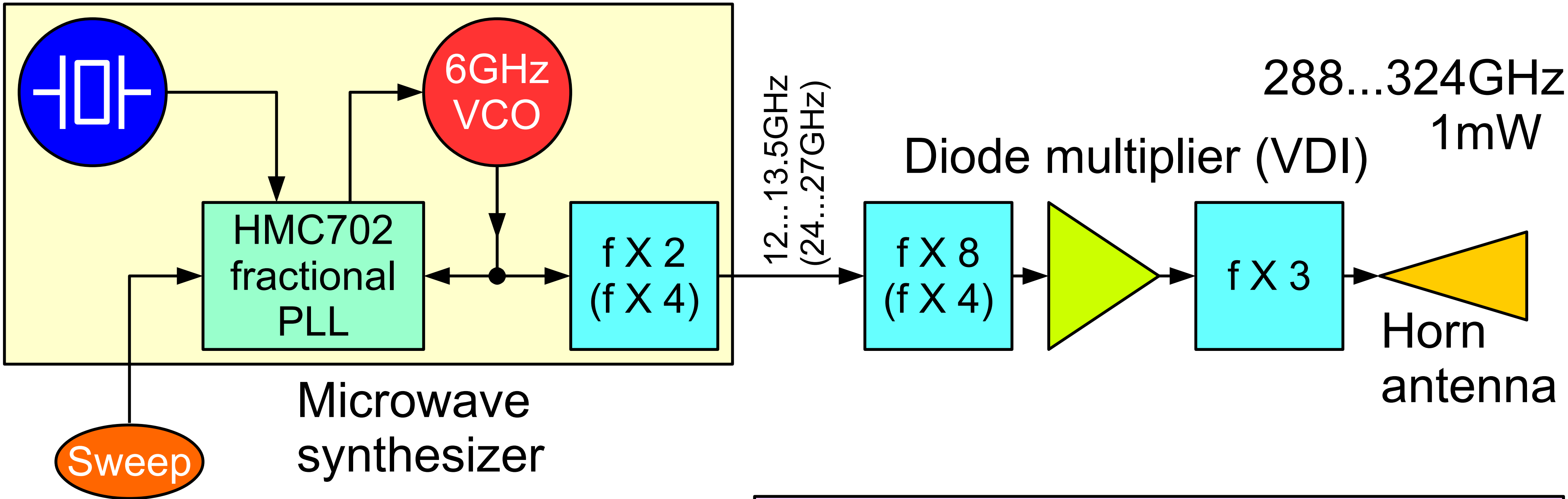
Active device	Noise temperature
Schottky diode	~300K
Transistor (BJT or FET)	~300K
Tunnel diode	~300K
Gunn diode	~300K
Vacuum tube	~10000K
Avalanche diode (Impatt diode)	~3000000K

Resonator	Q_L
RC (~BWO) tunable (VCO)!	~1
LC (~EIK) tunable or fixed!	~30
YIG @3GHz tunable!	~300
Metal cavity @3GHz fixed!	~3000
Ceramic dielectric @3GHz fixed!	~3000
Quartz crystal @100MHz fixed!	~30000
Electro-optical delay @6GHz fixed!	~100000
Sapphire dielectric @6GHz fixed!	~300000

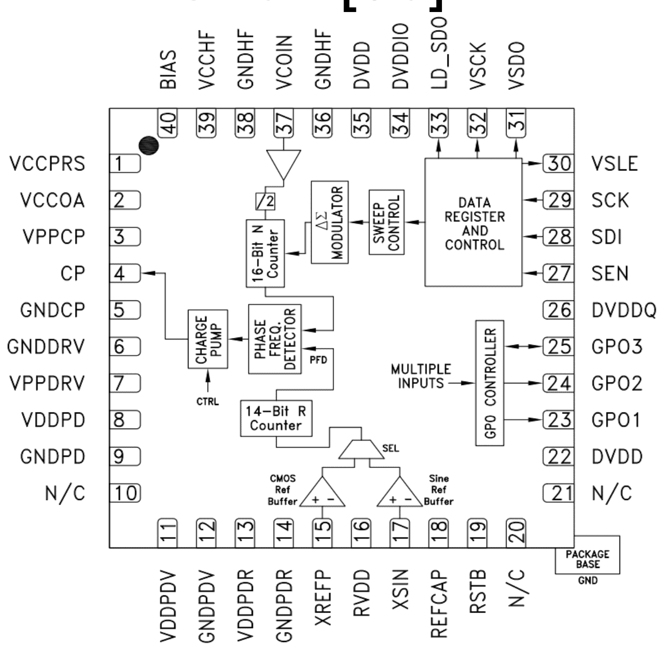
23 - Active-device noise and loaded-resonator quality

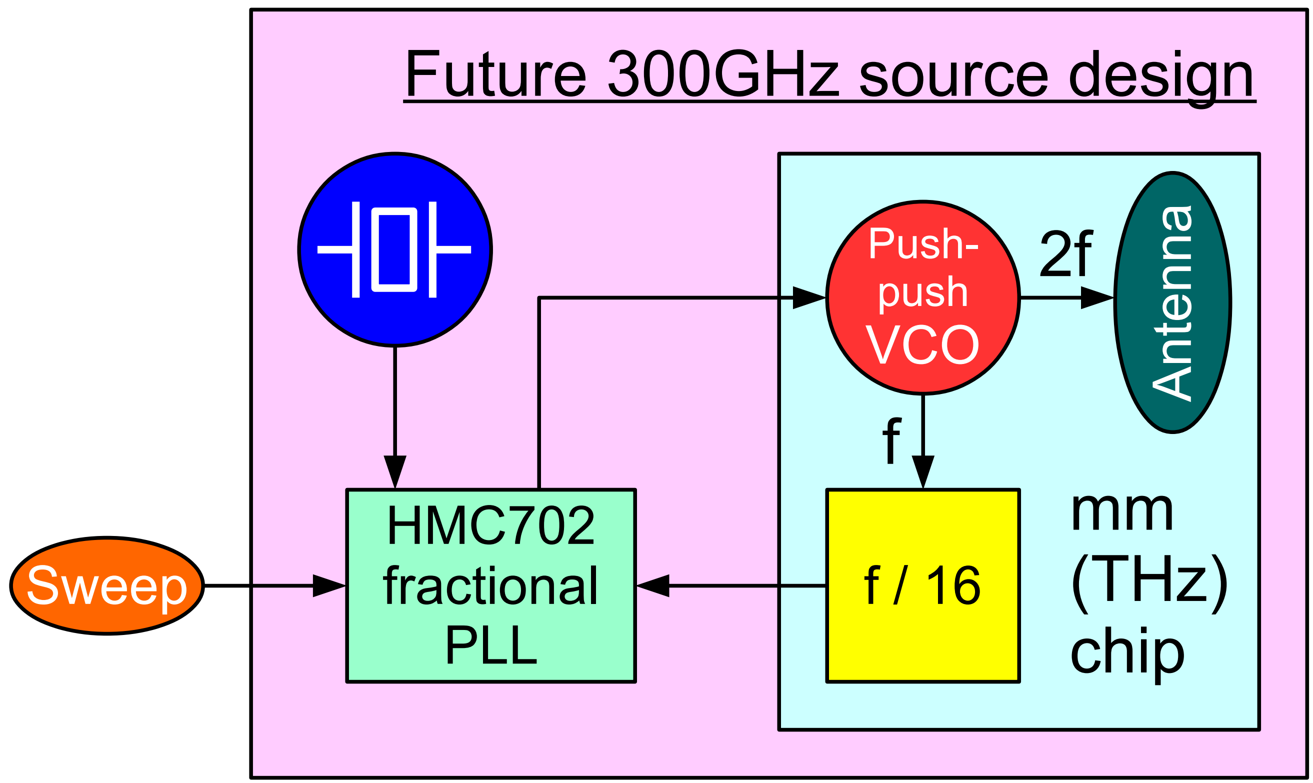


24 - Phase-locked-loop (PLL) synthesizer

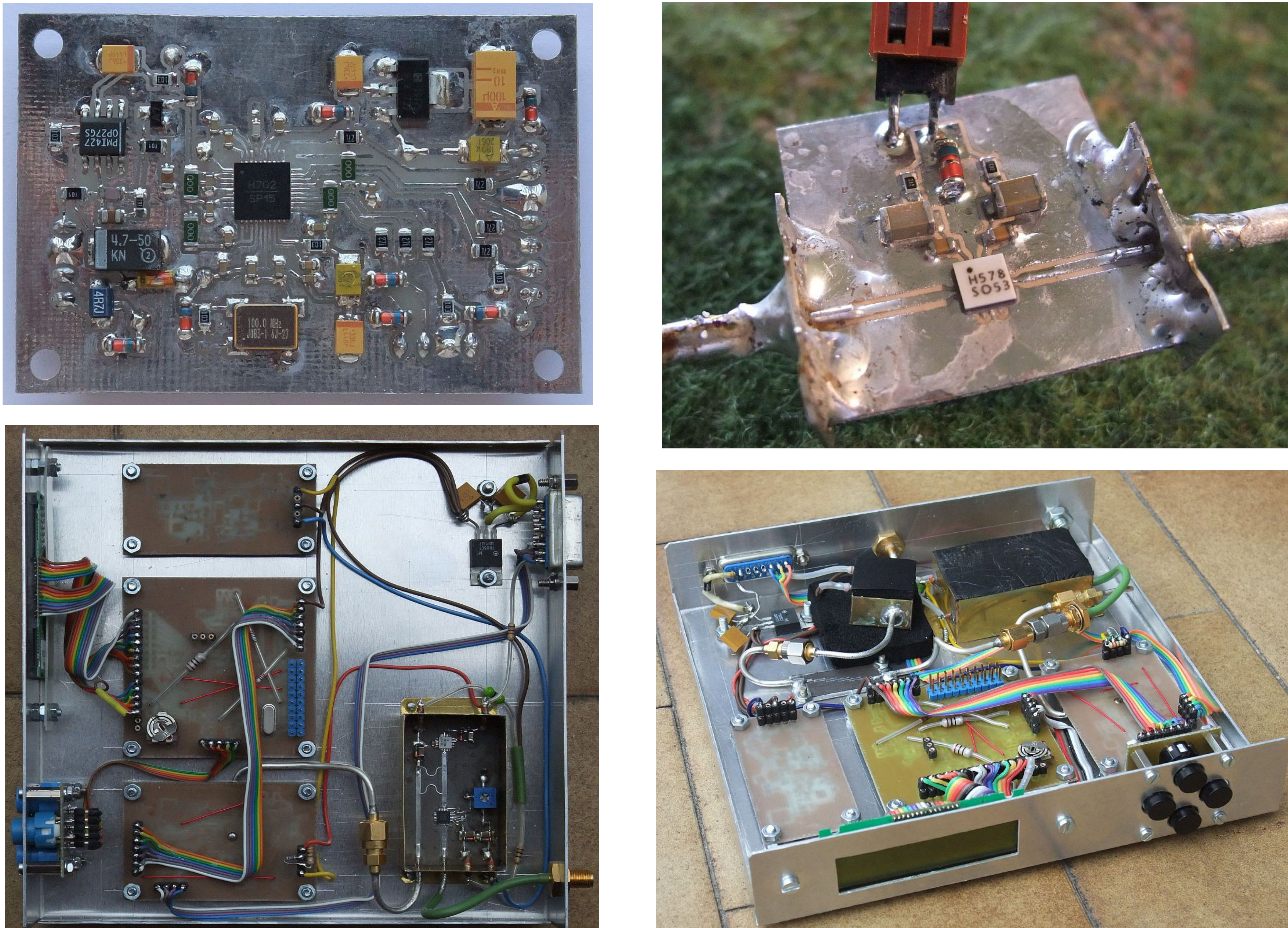


HMC702 [36]





25 - Millimeter source for a high-resolution FM radar



26 - Microwave synthesizer for a high-resolution FM radar

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