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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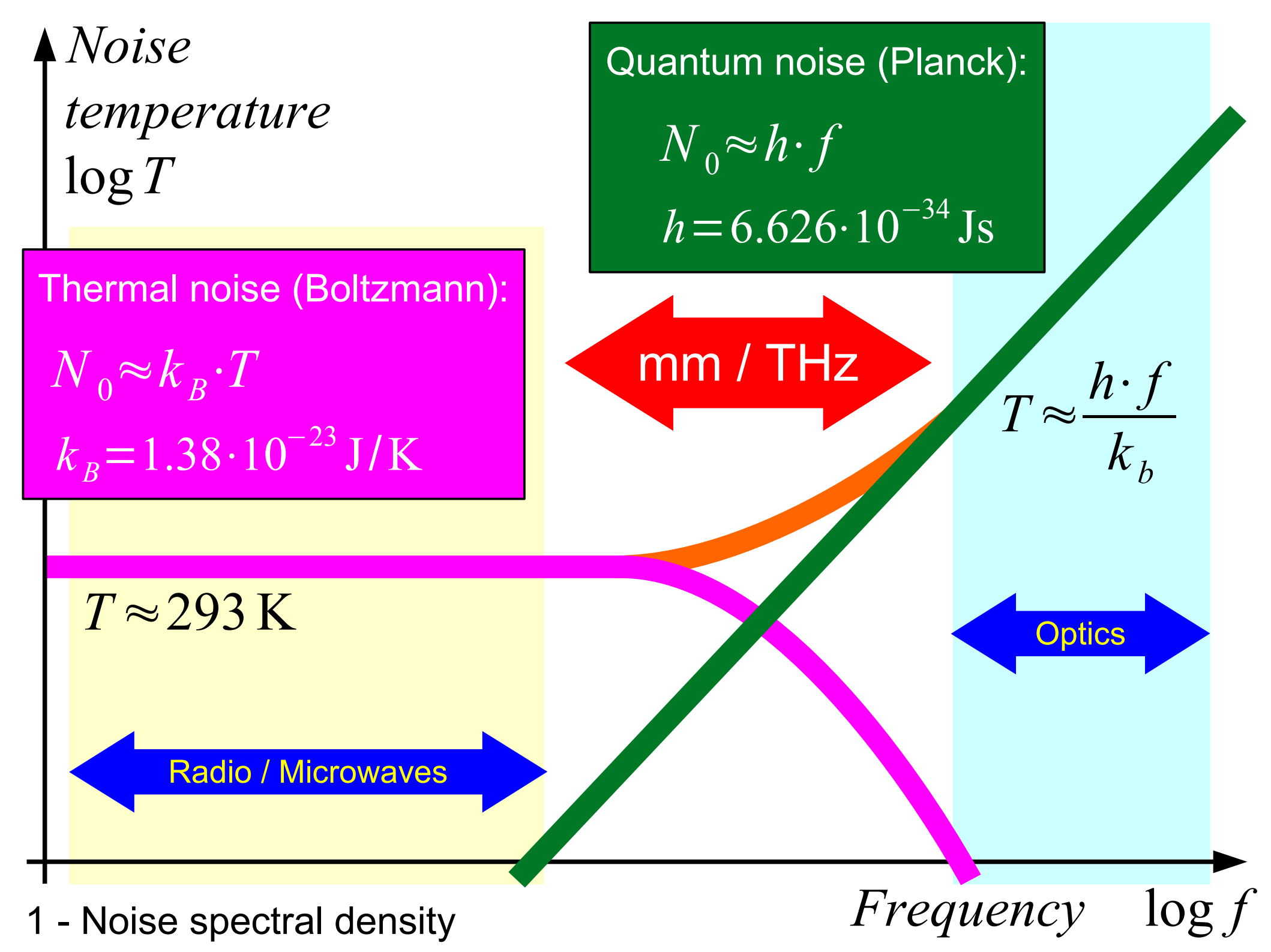
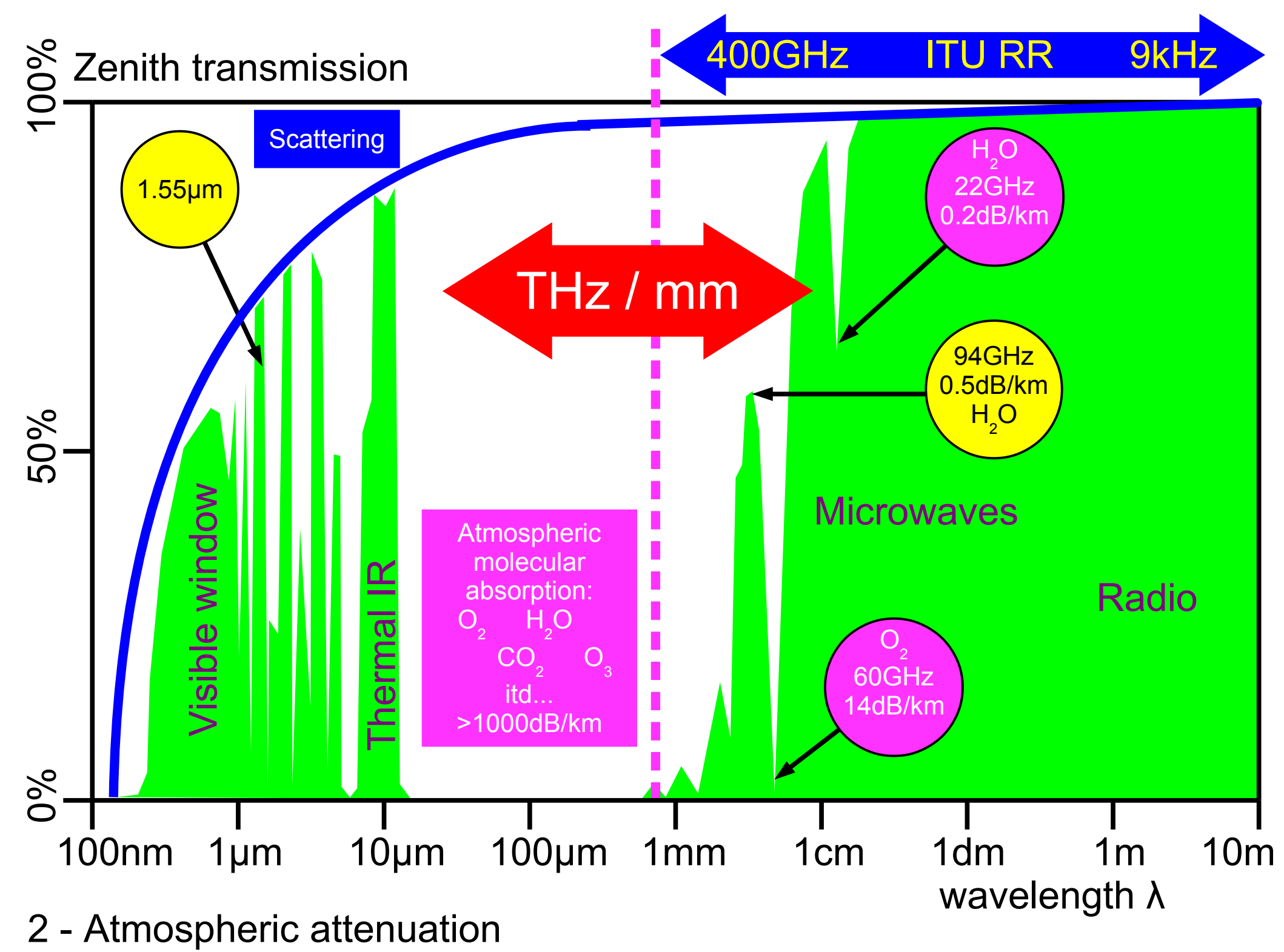
List of slides: MILLIMETER SOURCES


Noise
temperature
log T
Quantum noise (Planck):
$N_0 \approx h \cdot f$
$h = 6.626 \cdot 10^{-34}$ Js
Thermal noise (Boltzmann):
$N_0 \approx k_B \cdot T$
$k_B = 1.38 \cdot 10^{-23}$ J/K
mm / THz
$T \approx \frac{h \cdot f}{k_b}$
$T \approx 293$ K
Optics
Radio / Microwaves
1 - Noise spectral density
Frequency
log f

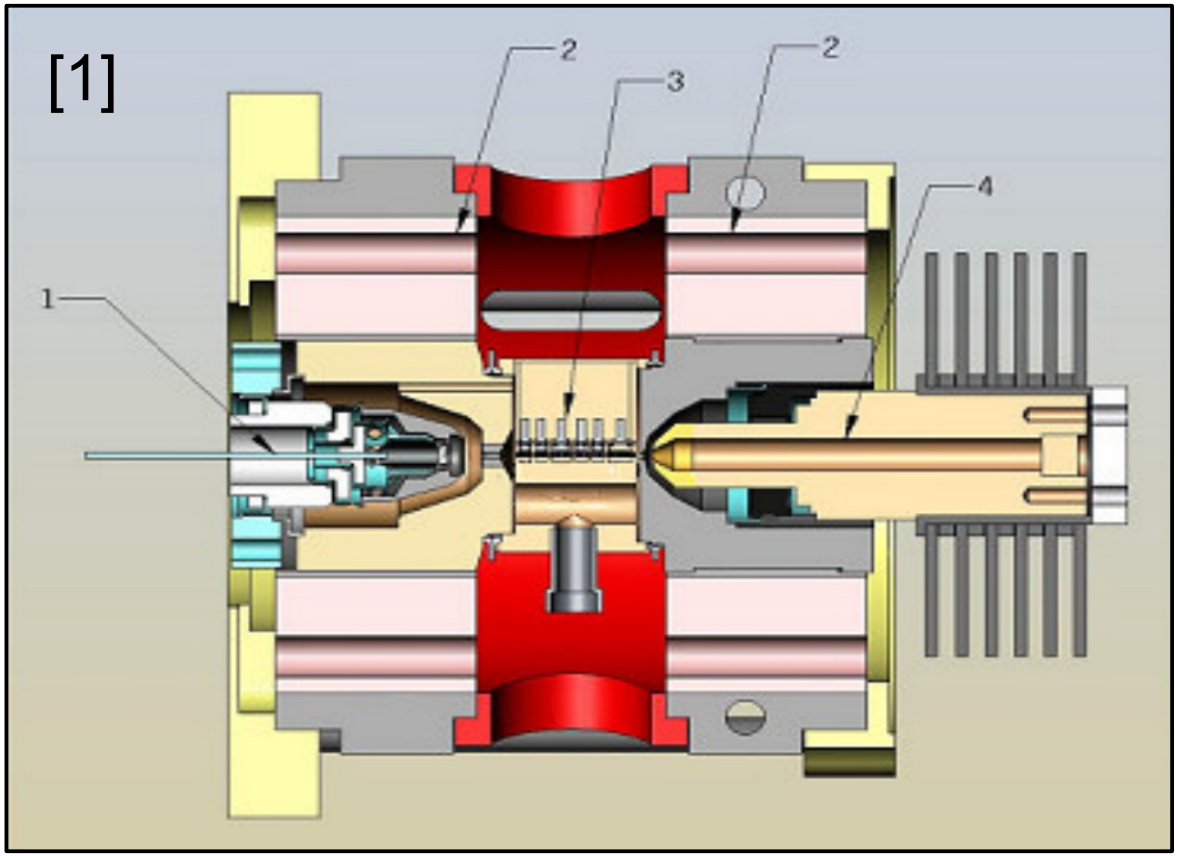


2 - Atmospheric attenuation

Slow-wave vacuum tube

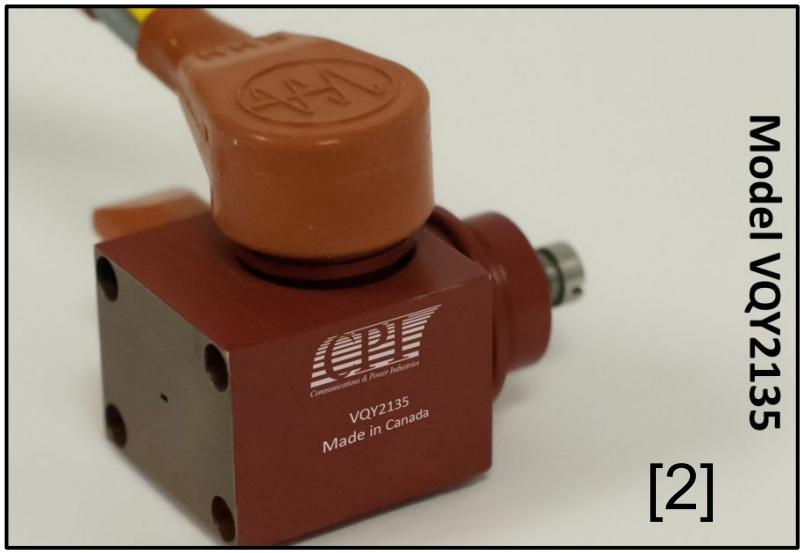
Narrowband electronically tunable (voltage U)

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

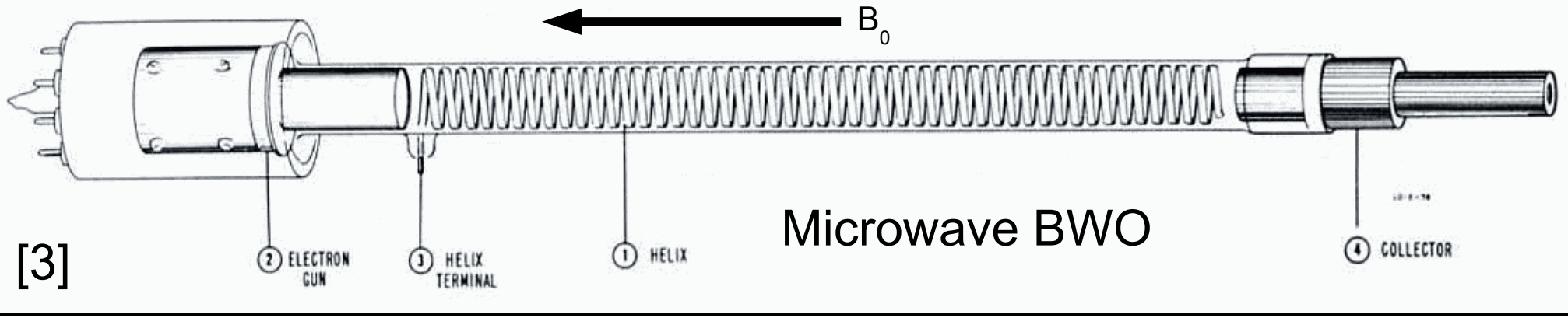


mm EIO

1 el. gun
2 magnet
3 cavities
4 collector



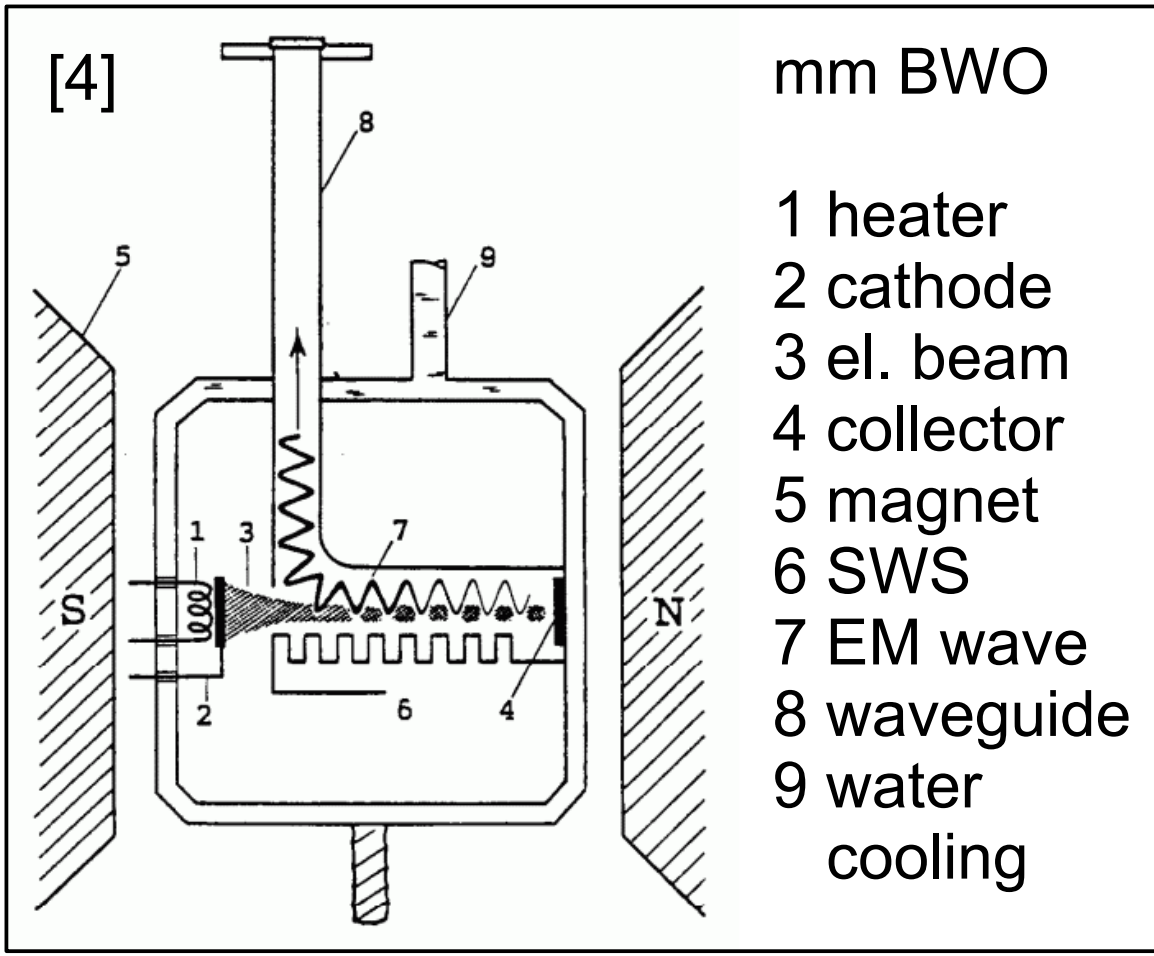
3 - Extended Interaction Klystron / Oscillator (EIK / EIO)



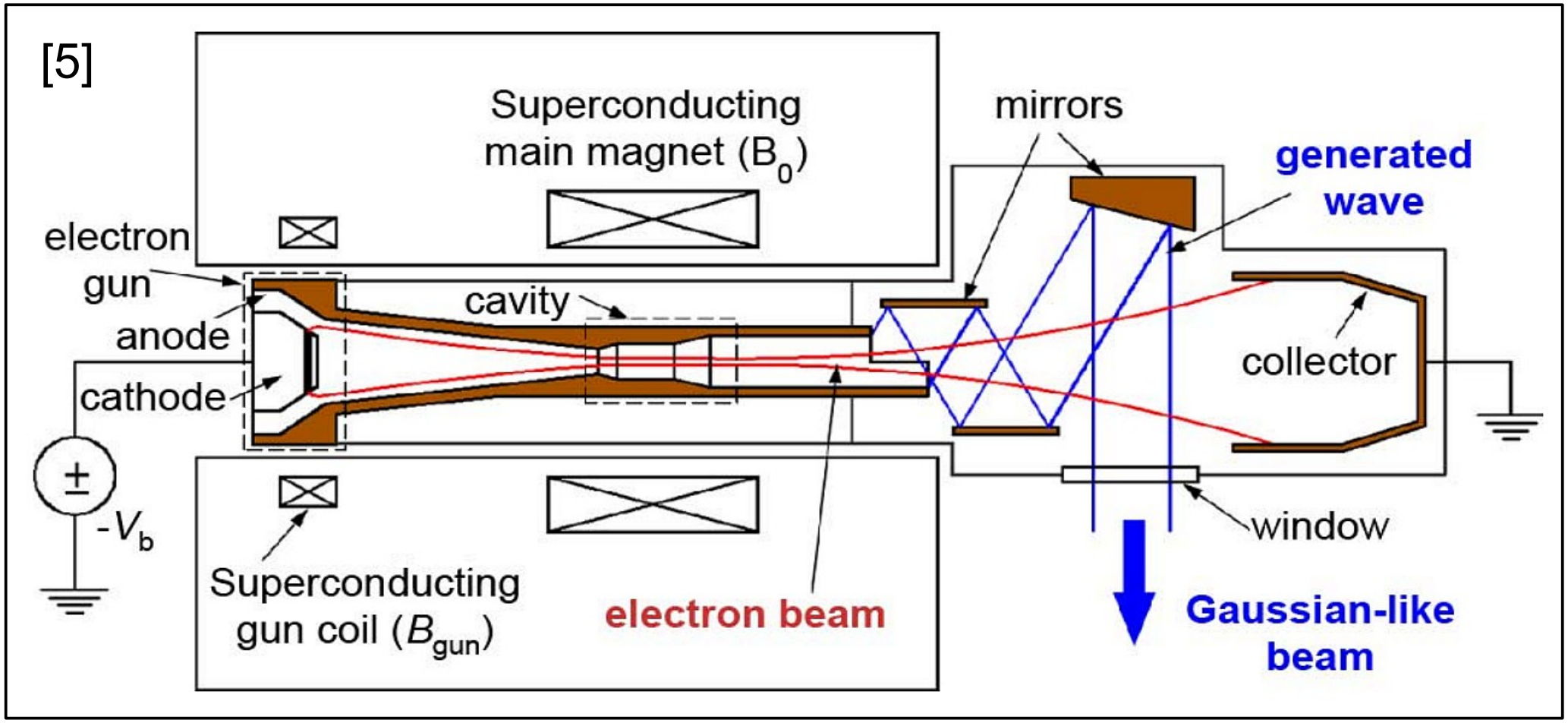
Slow-wave vacuum tube

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



4 - Bacward-Wave Oscillator (BWO or Carcinotron)

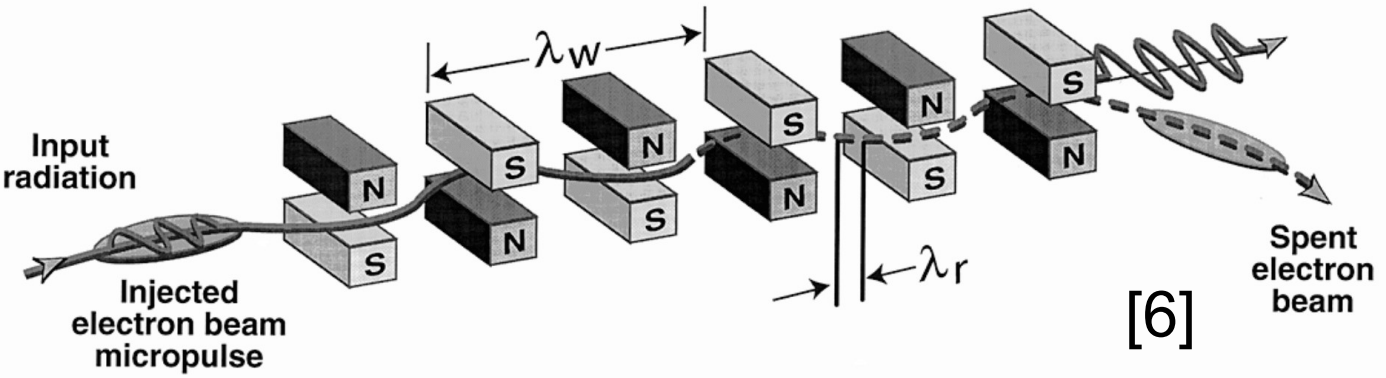


$$f = \frac{|Q_e| B_0}{2\pi m_e}$$

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

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

Wiggler (undulator)



[6]

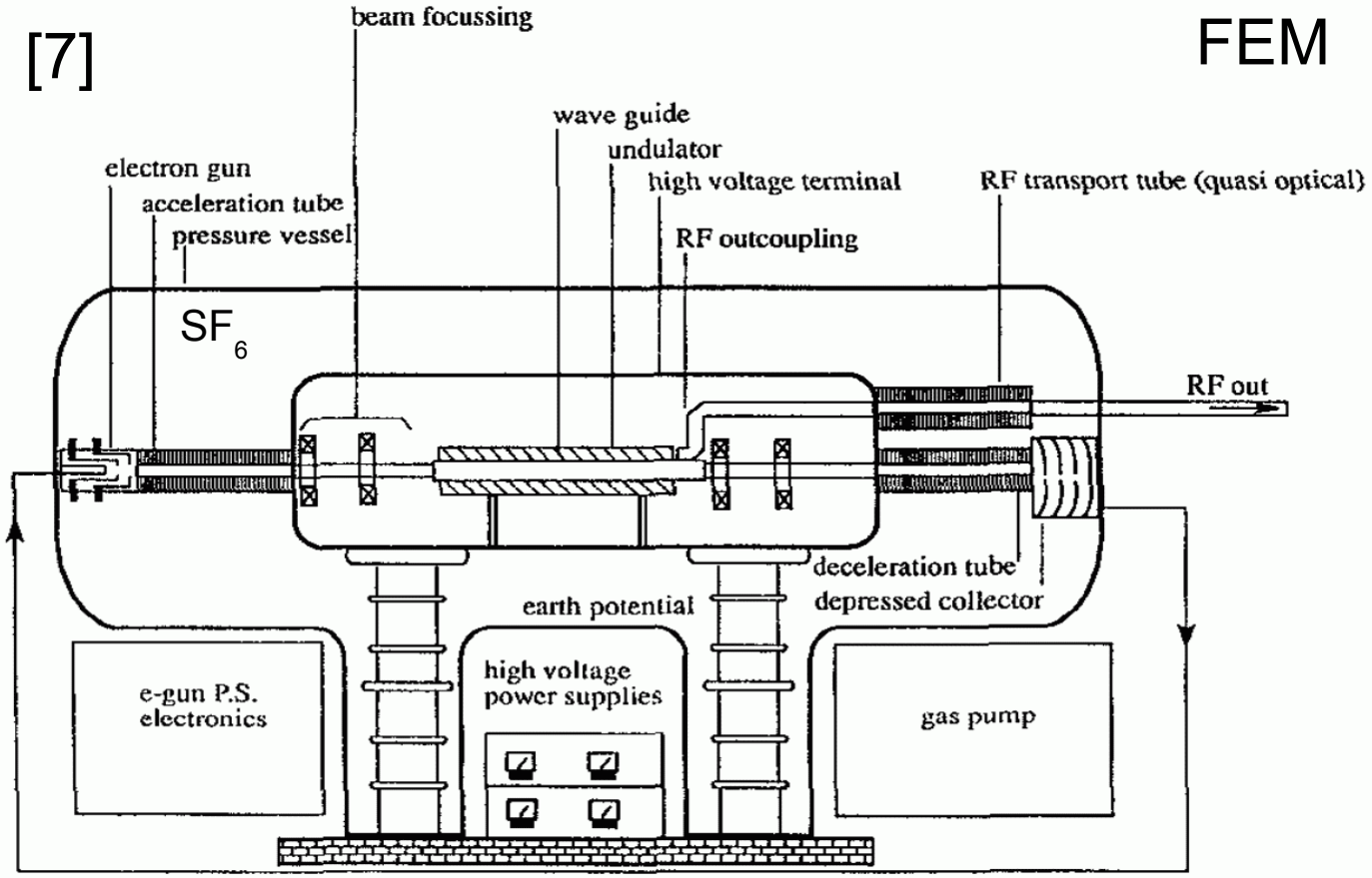
$$\lambda_r \approx \frac{\lambda_w}{2\gamma^2}$$

Lorentz

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

FEM

[7]



Fast-wave vacuum device

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

Widely tunable (U)

Amplification of mm waves requires U ≈ 2...6 MV

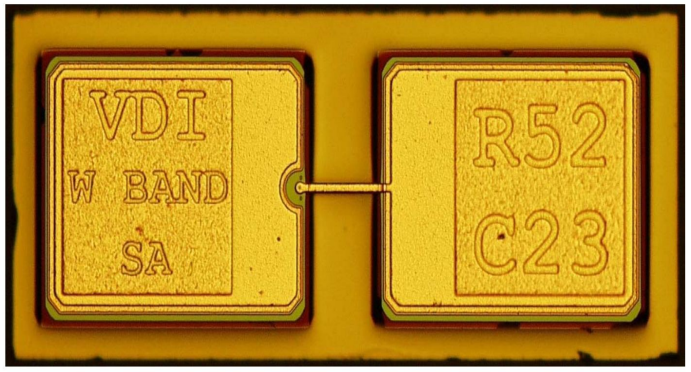
6 - Free-Electron Laser (FEL) or Maser (FEM)

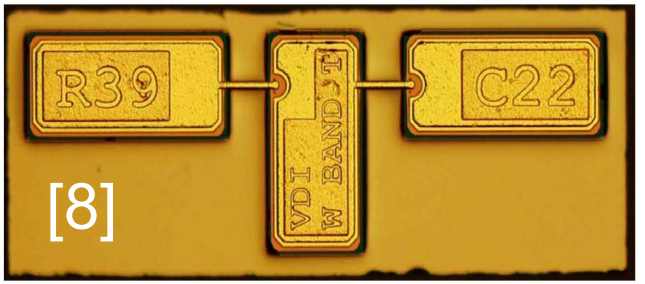
Semiconductor	Bandgap ΔW [eV]	Dielectric strength E_{MAX} [V/cm]	Electron mobility μ_n [cm^2/Vs]	Hole mobility μ_p [cm^2/Vs]
PbS	0.37	(breakdown<2V)	600	200
Se	1.95	(breakdown<25V)	0.005	0.14
PbSe	0.27		900	700
PbTe	0.32		1700	930
Cu_2O	2.137	(breakdown<8V)	0.2	0.1
Si	1.11	$3 \cdot 10^5$	1400	450
Ge	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

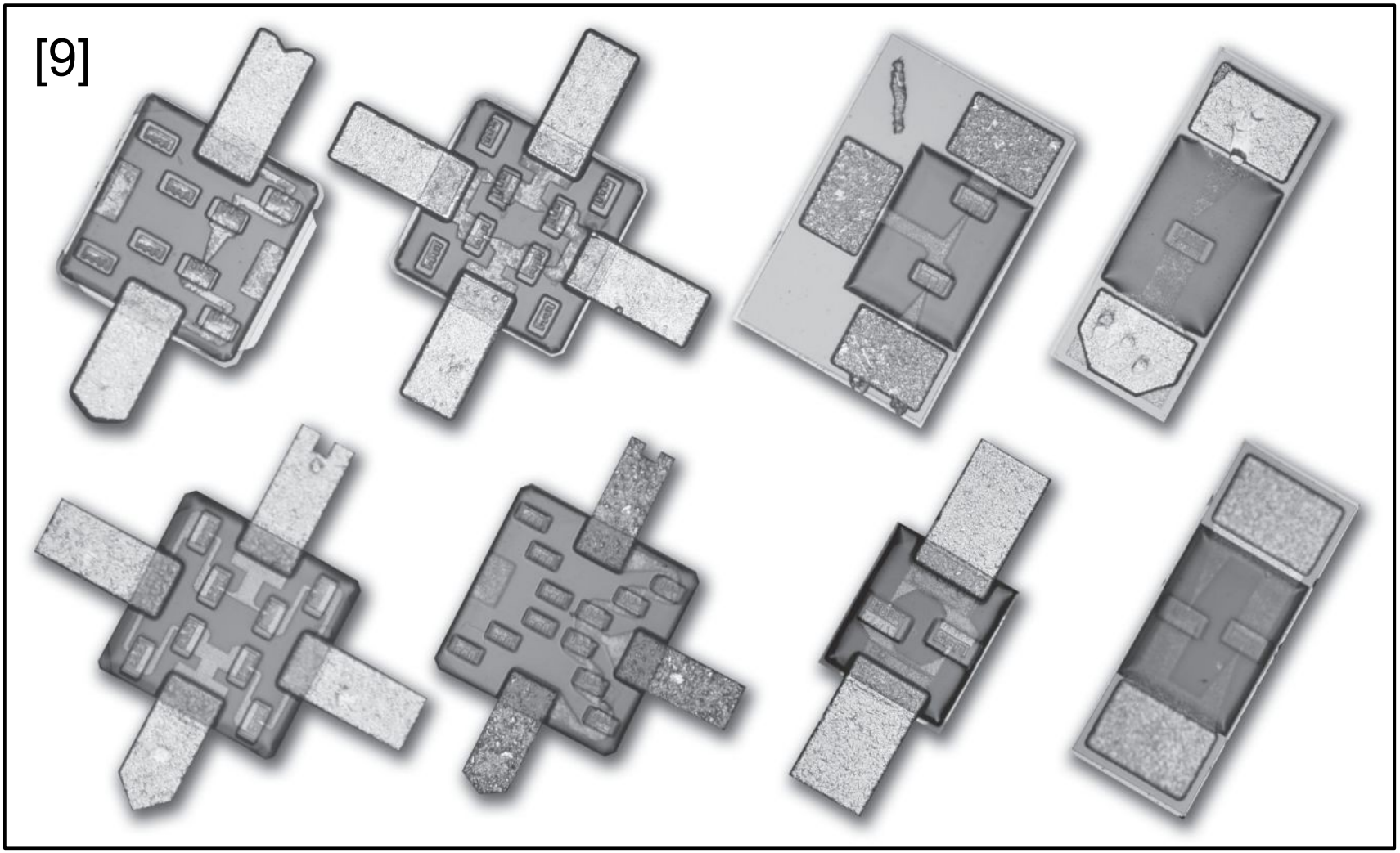
7 - Electrical properties of semiconductors (1)

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)







$U_F \approx 0.7V$
$@I_F = 1mA$

$U_R \approx 5V...$
$...10V$

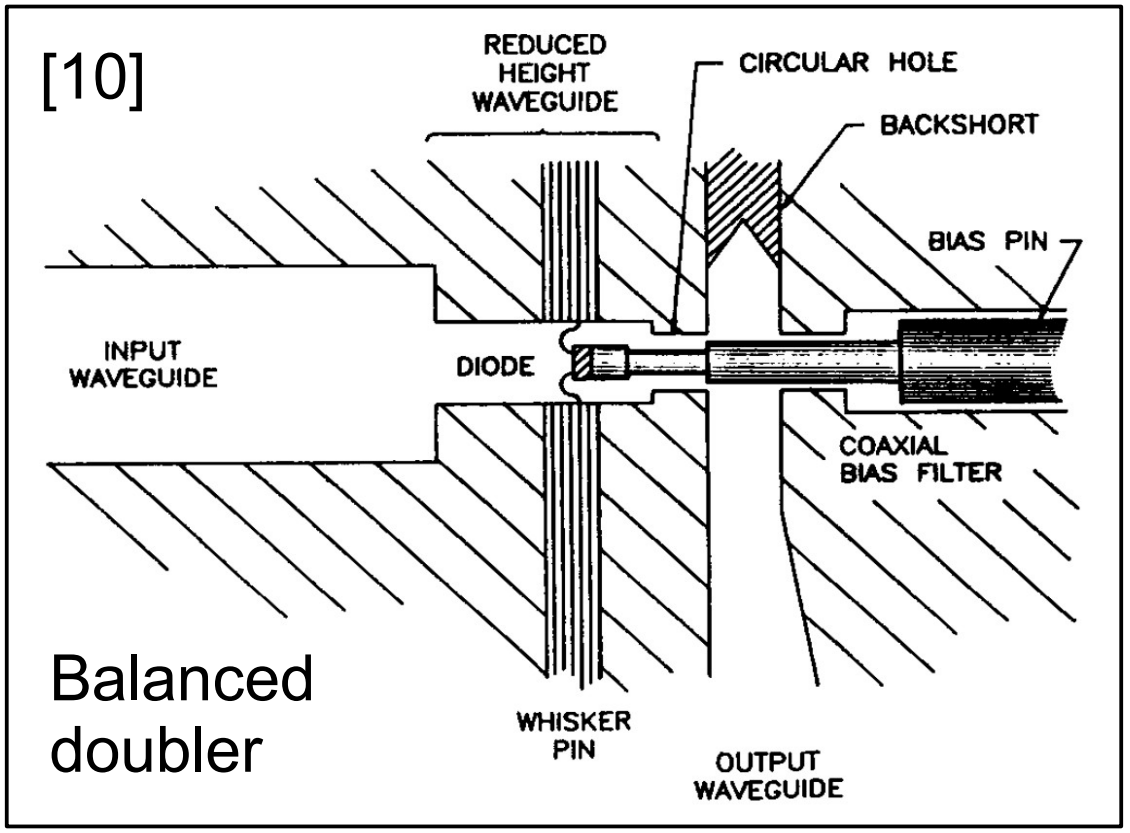
$C_J \approx 0.04pF$

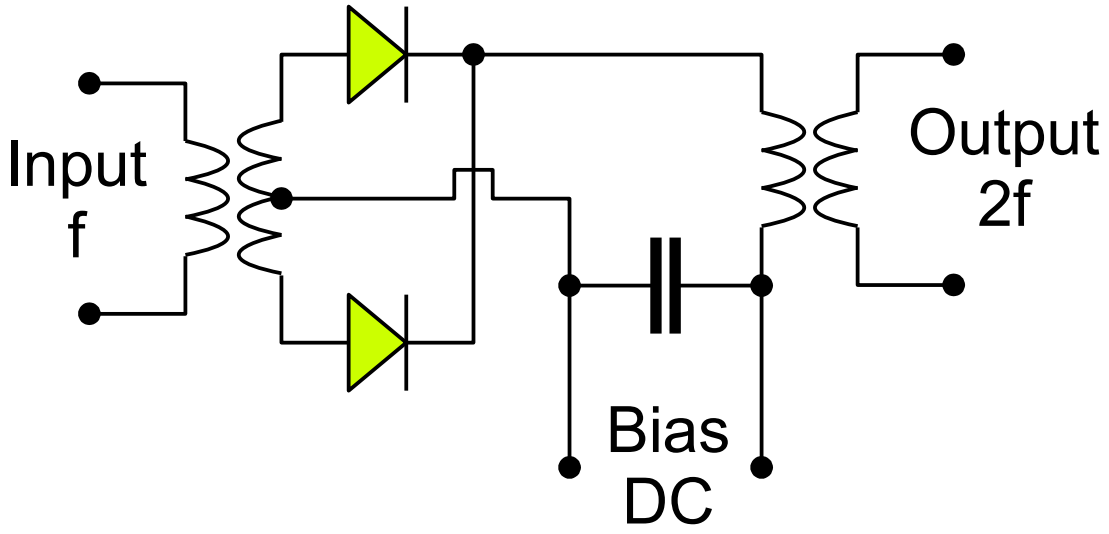
$R_S \approx 5\Omega$

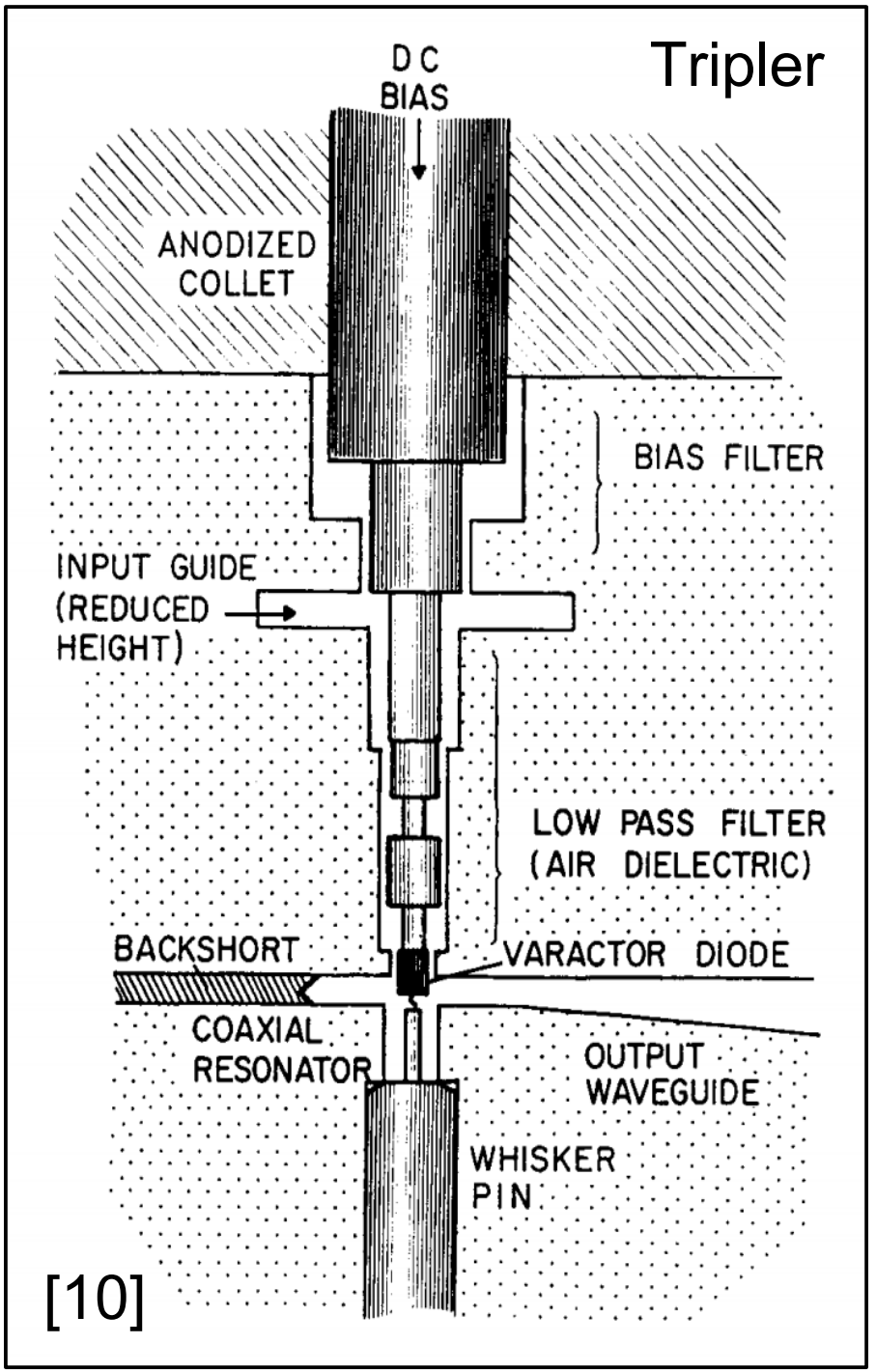
$\eta \approx 10\%$ (2f)

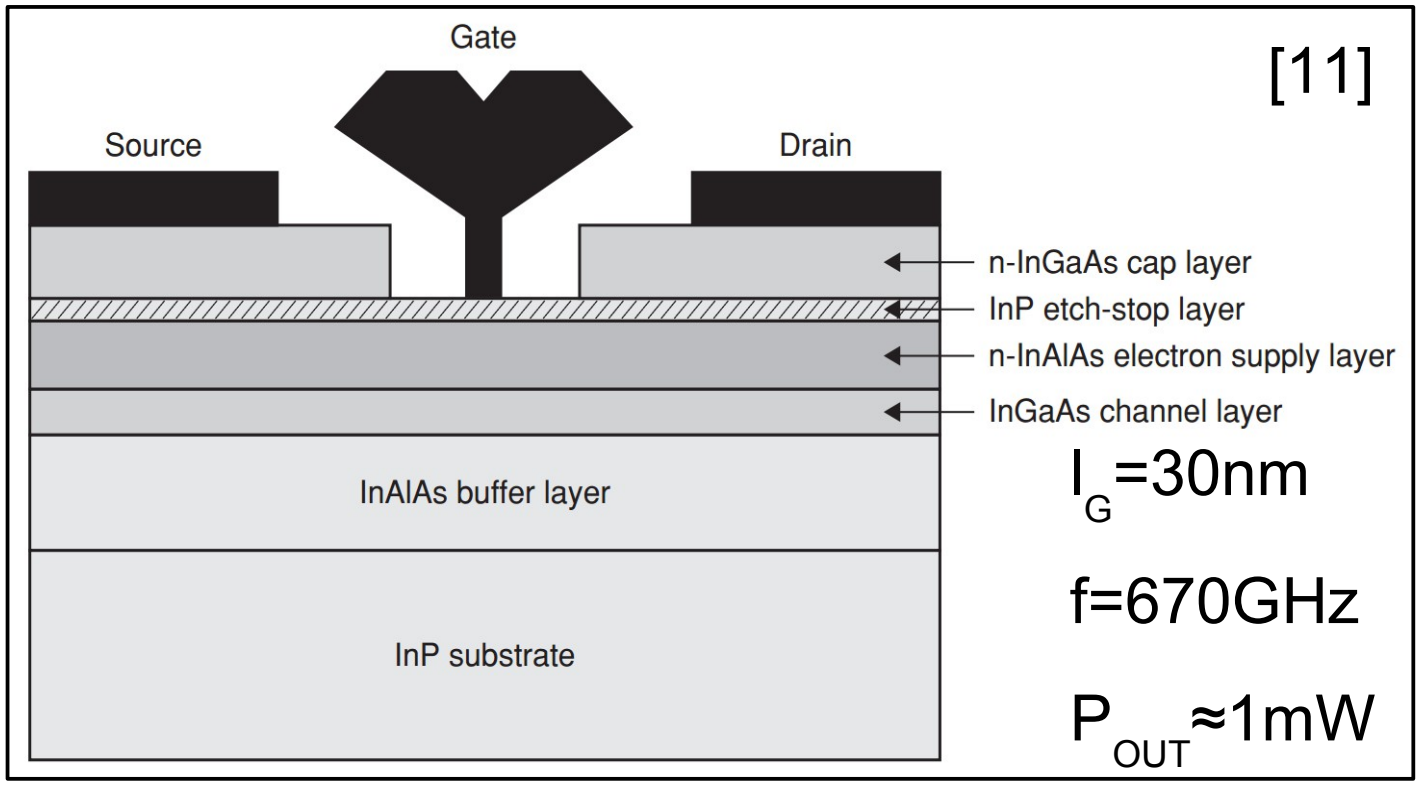
$\eta \approx 3\%$ (3f)

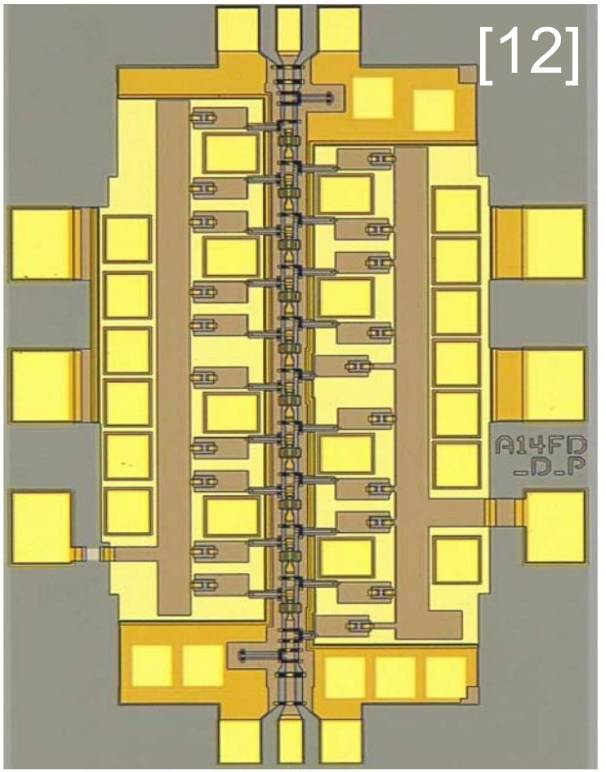
9 - GaAs flip-chip and beam-lead Schottky diodes

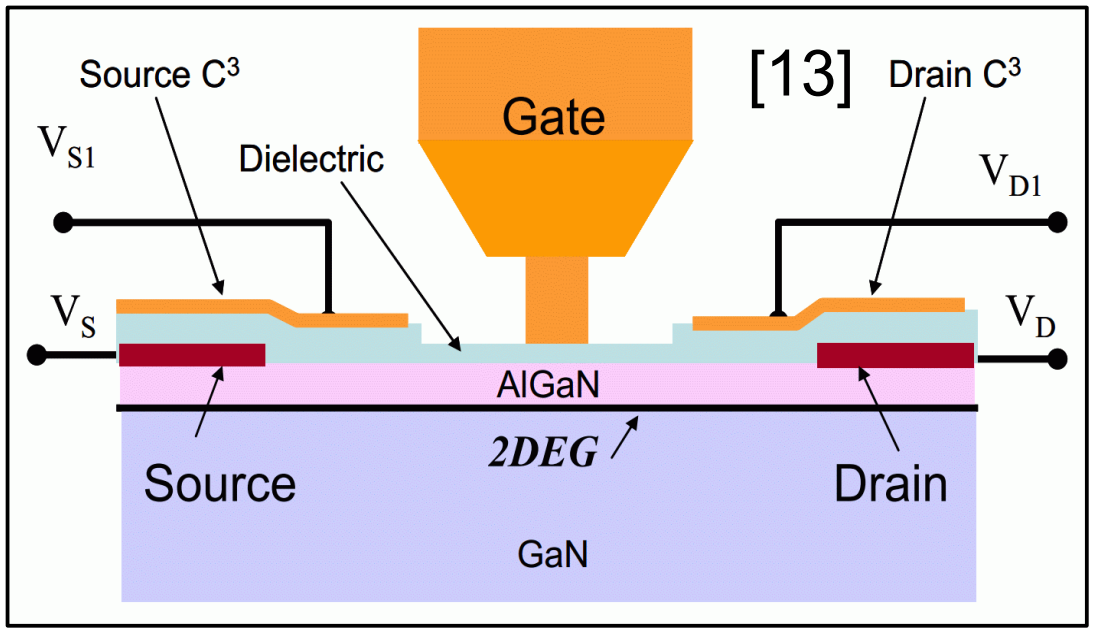

[10]
REDUCED HEIGHT WAVEGUIDE
CIRCULAR HOLE
BACKSHORT
BIAS PIN
INPUT WAVEGUIDE
DIODE
COAXIAL BIAS FILTER
WHISKER PIN
OUTPUT WAVEGUIDE
Balanced doubler

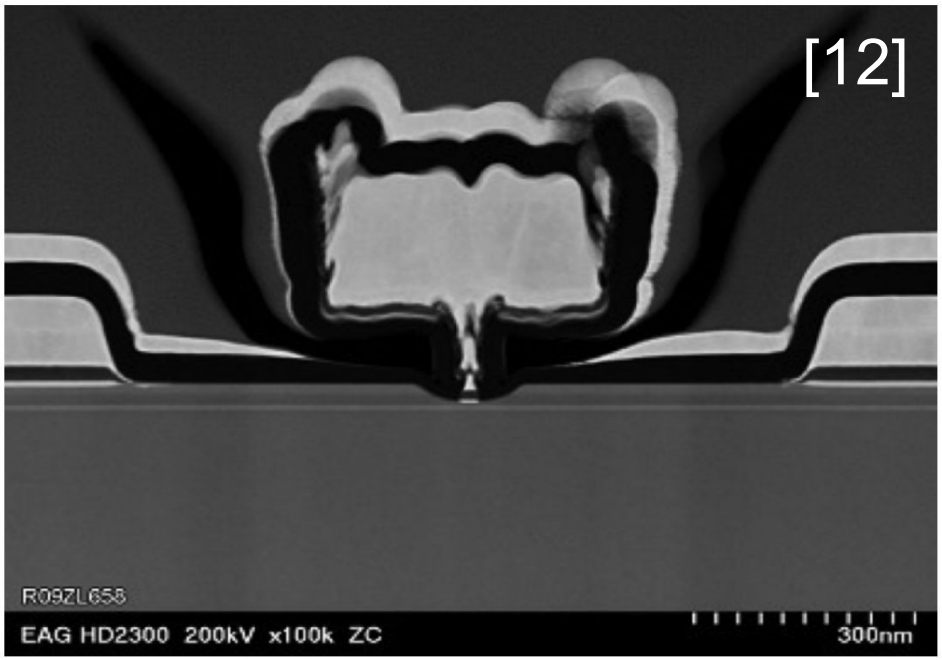

Input
f
Output
2f
Bias
DC


Tripler
DC BIAS
ANODIZED COLLET
BIAS FILTER
INPUT GUIDE (REDUCED HEIGHT)
LOW PASS FILTER (AIR DIELECTRIC)
BACKSHORT
VARACTOR DIODE
COAXIAL RESONATOR
OUTPUT WAVEGUIDE
WHISKER PIN
[10]



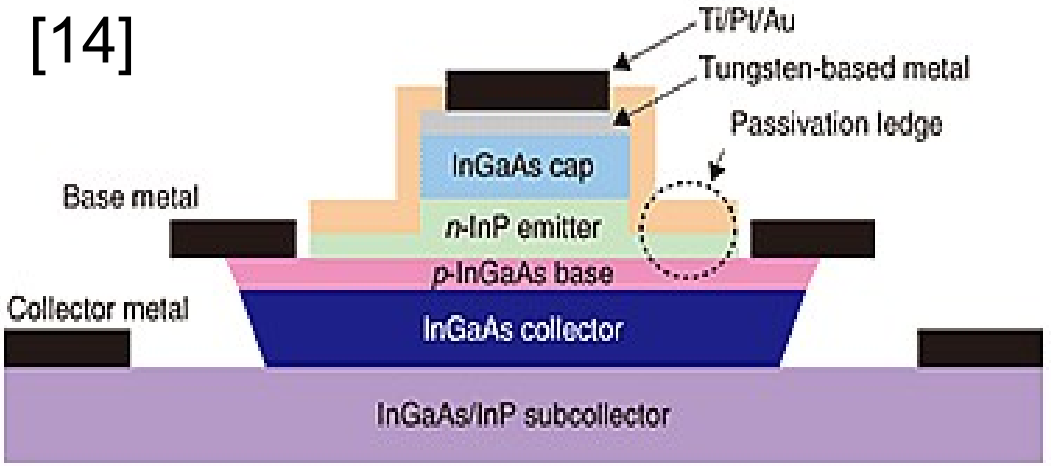




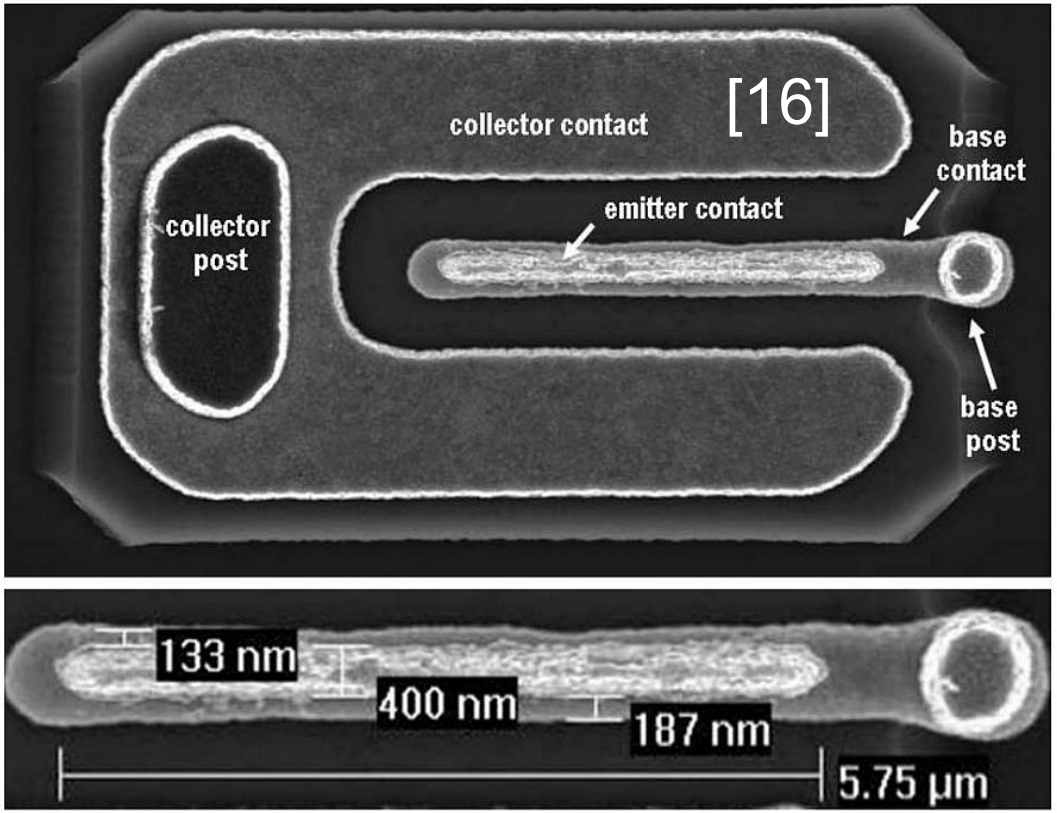


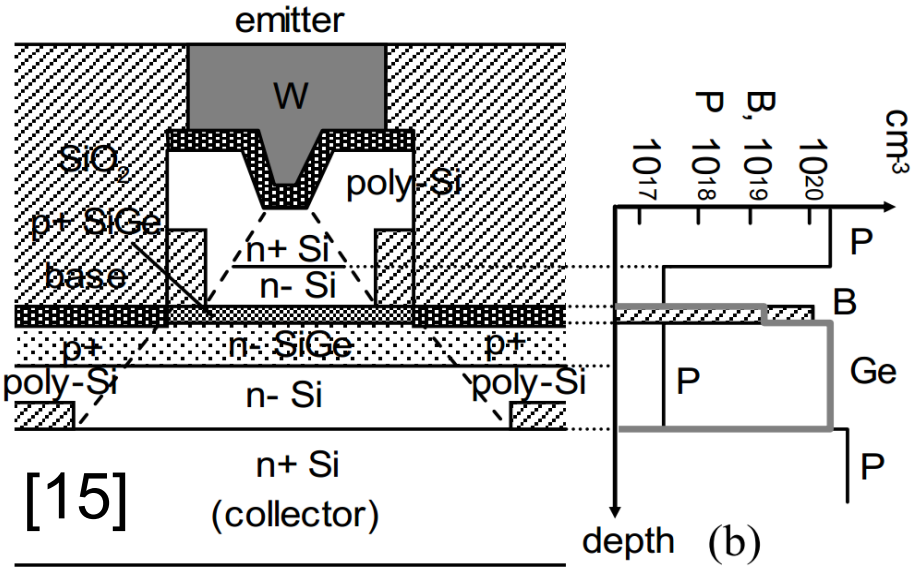
11 - InP / GaN High Electron Mobility Transistor (HEMT)

[14]

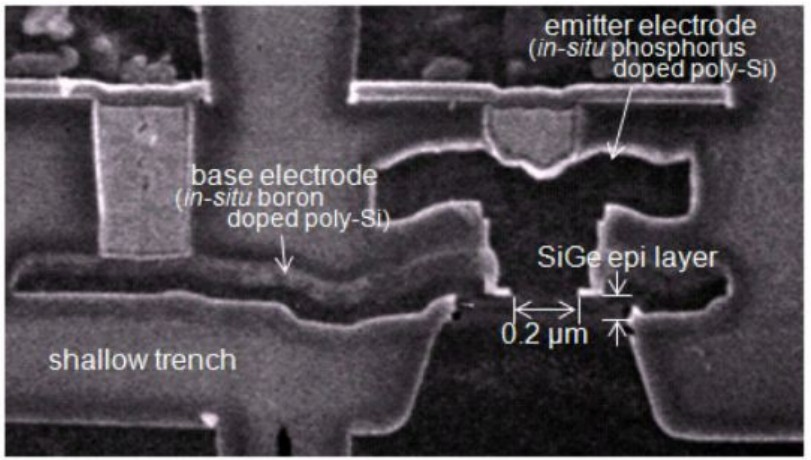


InP HBT

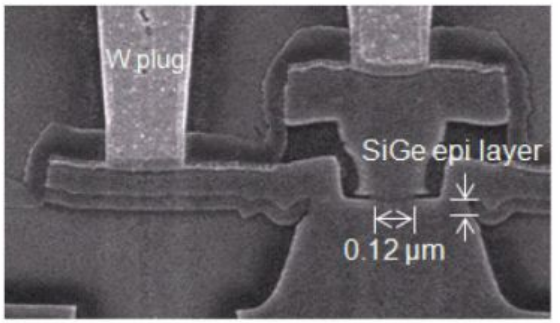




[15]

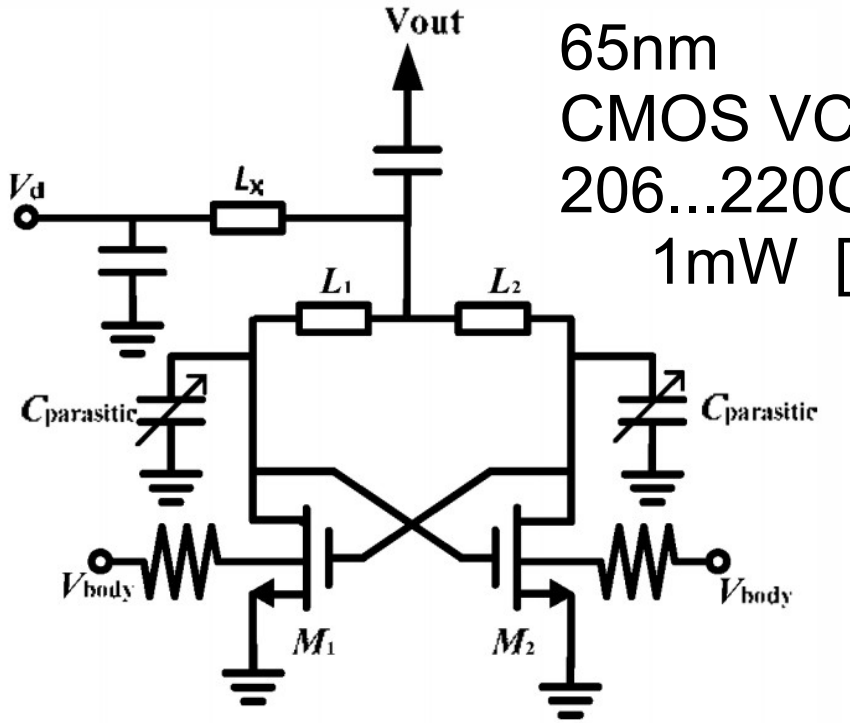


[17]

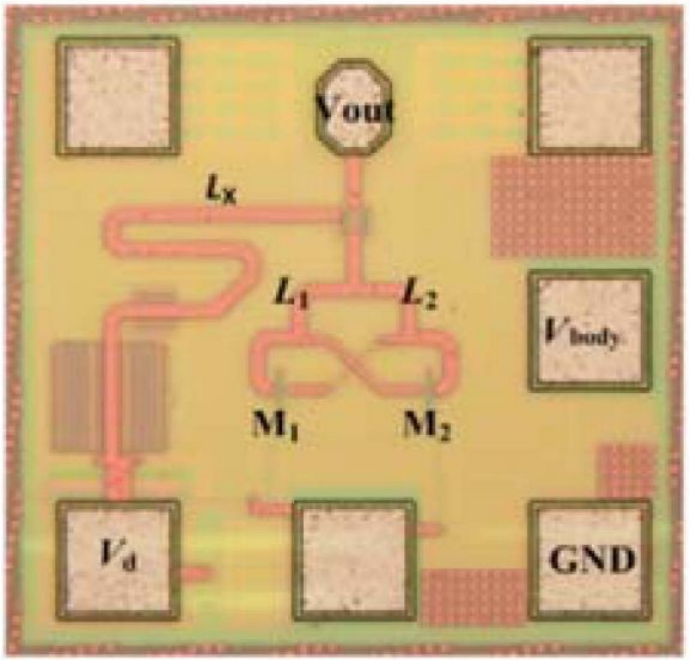


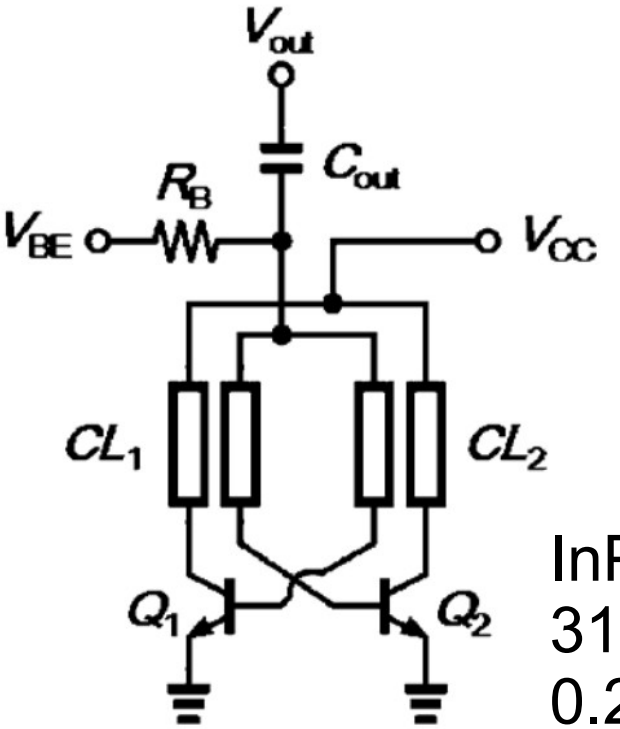
SiGe HBT

12 - InP / SiGe Heterostructure Bipolar Transistor (HBT)

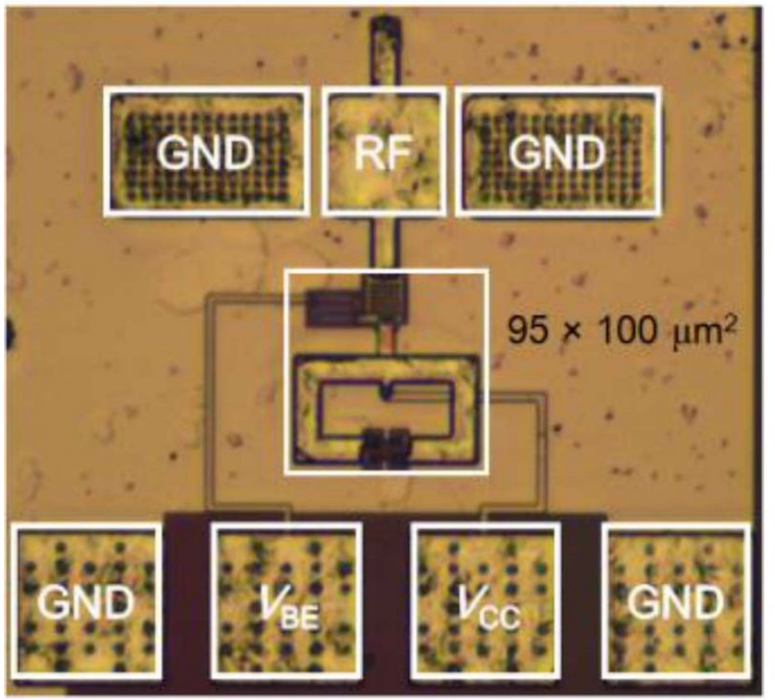


65nm
CMOS VCO
206...220GHz
1mW [18]





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



13 - Push-push oscillator / doubler