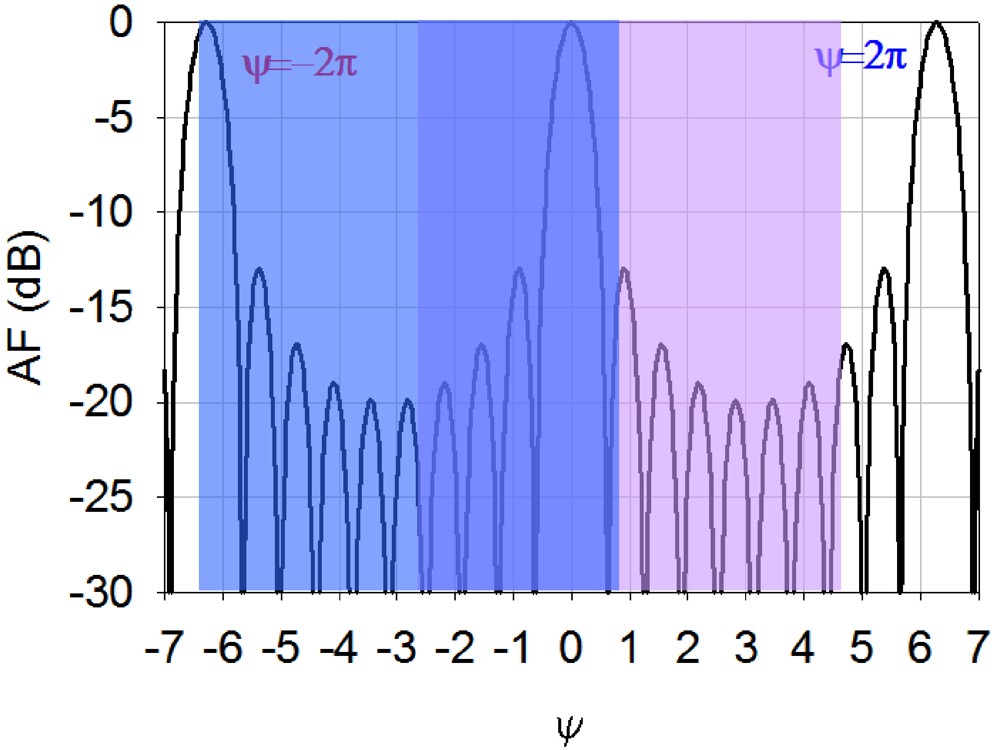
Spring 2019

EECE 588
Lecture 15

Prof. Wonbin Hong

Grating Lobes

- As you see, as we change the phase shift of each antenna, the beam can be scanned.
- This means that we are changing the visible region dynamically and moving it around.
- The manifestation of this is the change in the direction of maximum radiation or electronic beam steering.



POSTECH

Grating Lobes

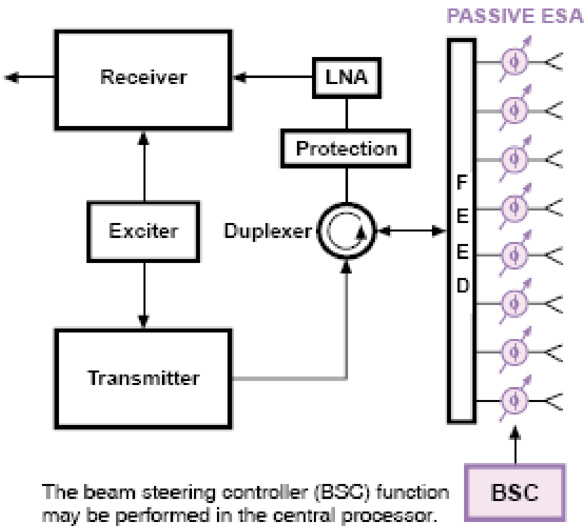
- To ensure that grating lobes are not excited we must ensure that the visible region only contains the main peak of the periodic array factor and not any other major peaks.
- To have the main beam of the antenna directed along θ_0, the required phase shift is $\beta = -kd\cos\theta_0$.
  - Remember that the peak occurs for $\psi = 0$.
- Therefore, we have to ensure that ψ is between $\pm 2\pi$ $(-2\pi < \psi < 2\pi)$.
- But maximum value of magnitude of ψ is $kd(1 + |\cos\theta|)$.
- Therefore, to have no grating lobes:

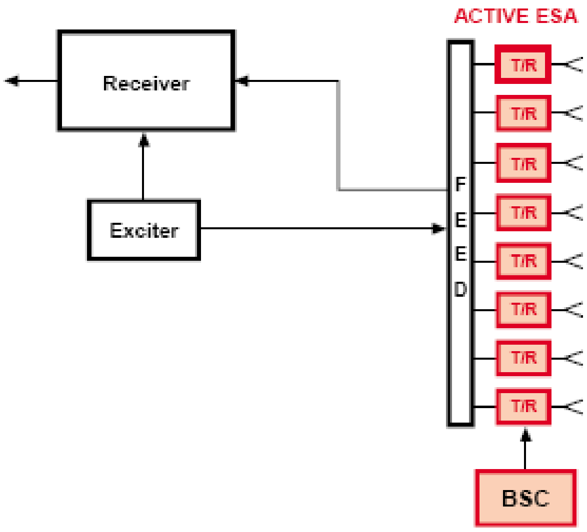
$$d < \frac{\lambda}{1 + |\cos\theta_0|}$$

POSTECH

Phased Array Architectures

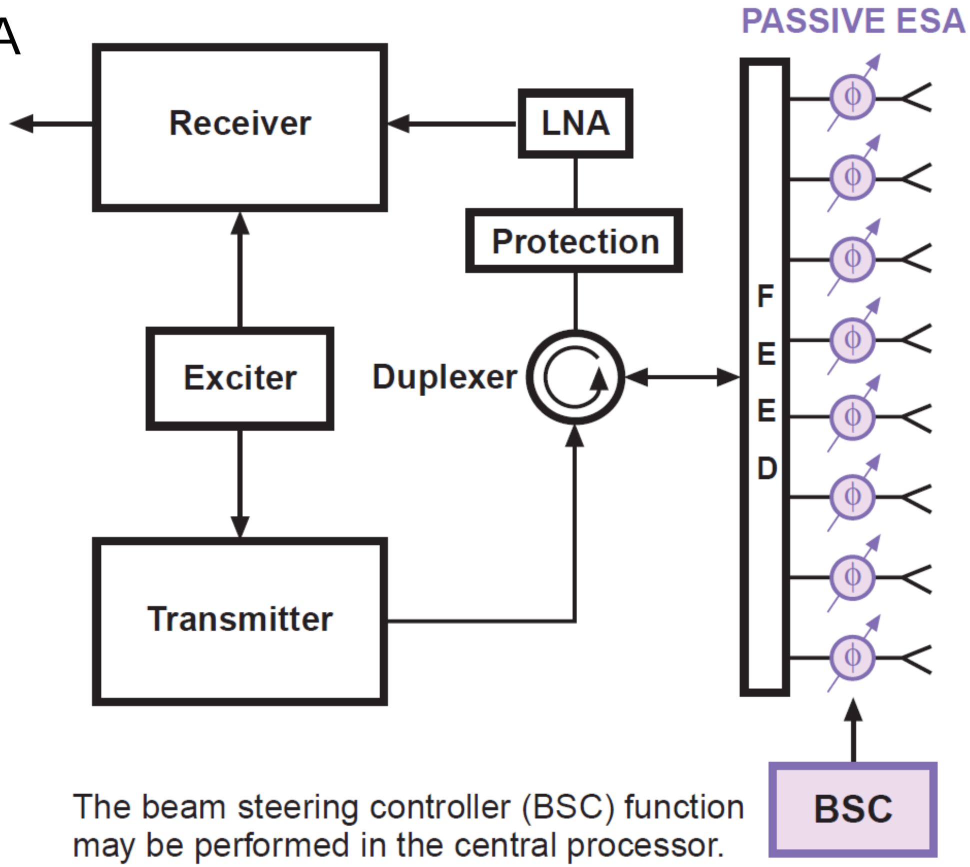
- Active Electronically Steered Antennas (AESA).
- Passive Electronically Steered Antennas (PESA).
- True-time-delay (TTD) ESAs.





Passive ESA

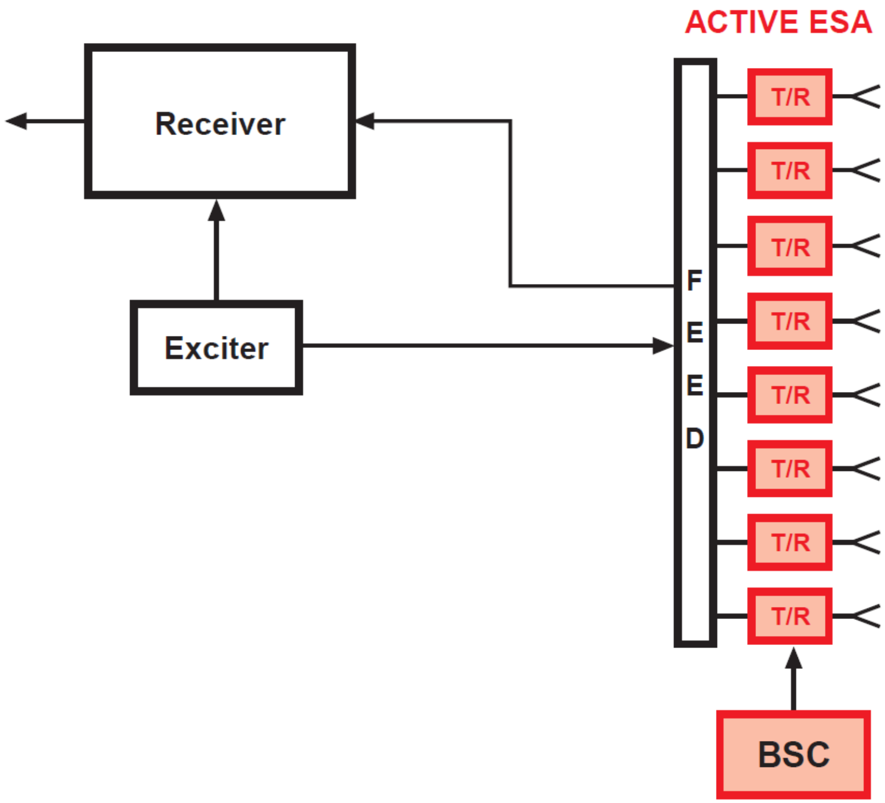
- PESA is simpler than the AESA but more complex than a mechanically steered array (MSA).
- It operates in conjunction with the same sort of central transmitter and receiver as the MSA.
- To steer the beam formed by the array, an electronically controlled phase shifter is placed immediately behind each radiator.
- The phase shifter is controlled either by a local processor called the *beam steering controller (BSC)* or by the central processor of the array.



The beam steering controller (BSC) function may be performed in the central processor.

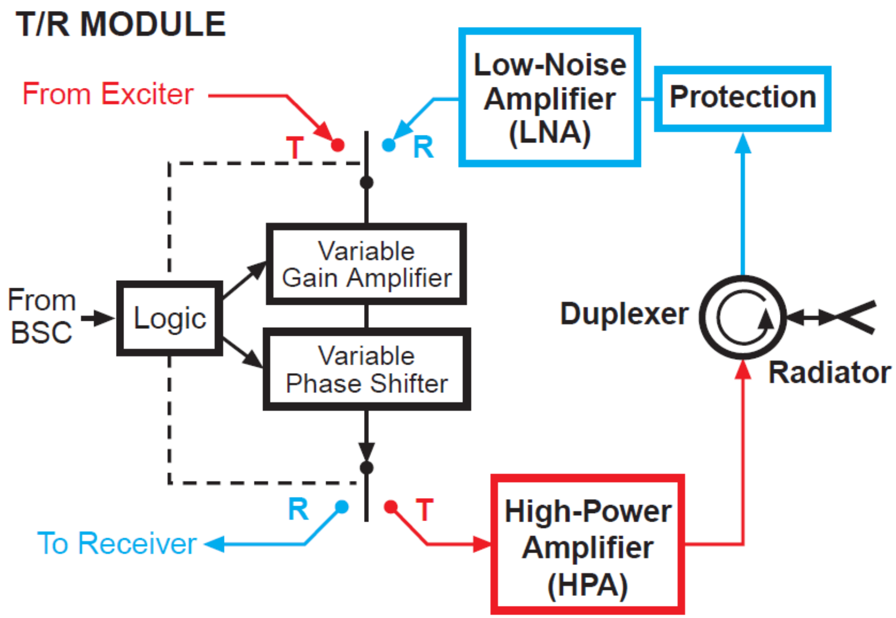
Active ESA

- The active ESA is an order of magnitude more complex than the passive ESA.
- Instead of a phase shifter, a tiny dedicated transmit/receive (T/R) module is placed directly behind each radiating element of the array.
- Within it, are both the transmitter power-amplifier function and the receiver front-end functions.



AESA

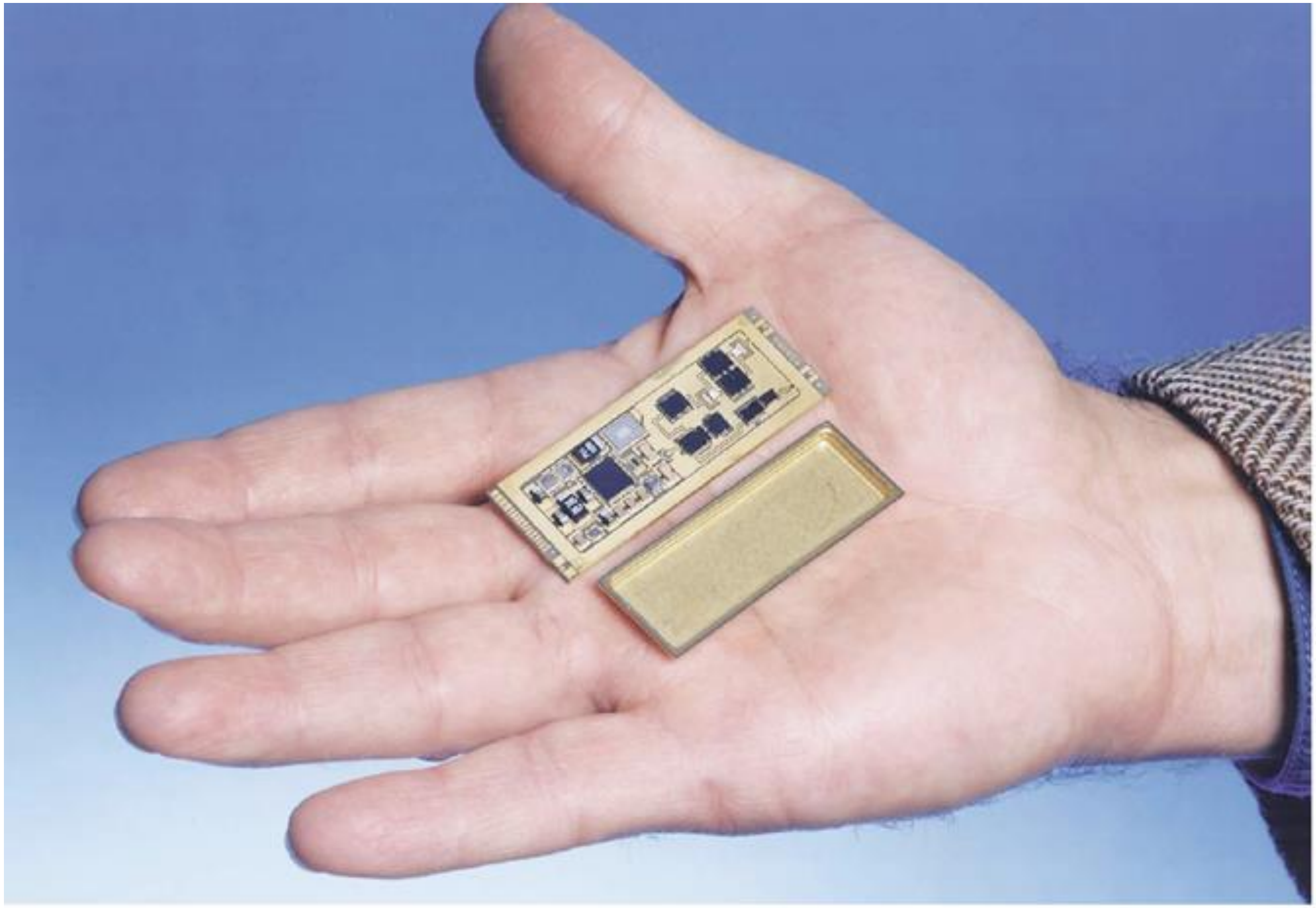
- The TR module is a complete 2-way radio system containing the following:
  - A multistage high power amplifier (HPA).
  - a duplexer (circulator).
  - a protection circuit to block any leakage of the transmitted pulses through the duplexer into the receiving channel.
  - a low-noise preamplifier (LNA) for the received signals.
- The RF input and output are passed through a variable gain amplifier and a variable phase shifter, which typically are time shared between transmission and reception.
- They, and the associated switches, are controlled by a logic circuit in accordance with commands received from the beam steering controller.
- To minimize the cost and the size, TR modules are usually implemented using integrated circuit technology.



5. Basic functional elements of a T/R module. Variable gain amplifier, variable phase shifter, and switches are controlled by the logic element. They may be duplicated for transmit and receive, or time shared as shown here.

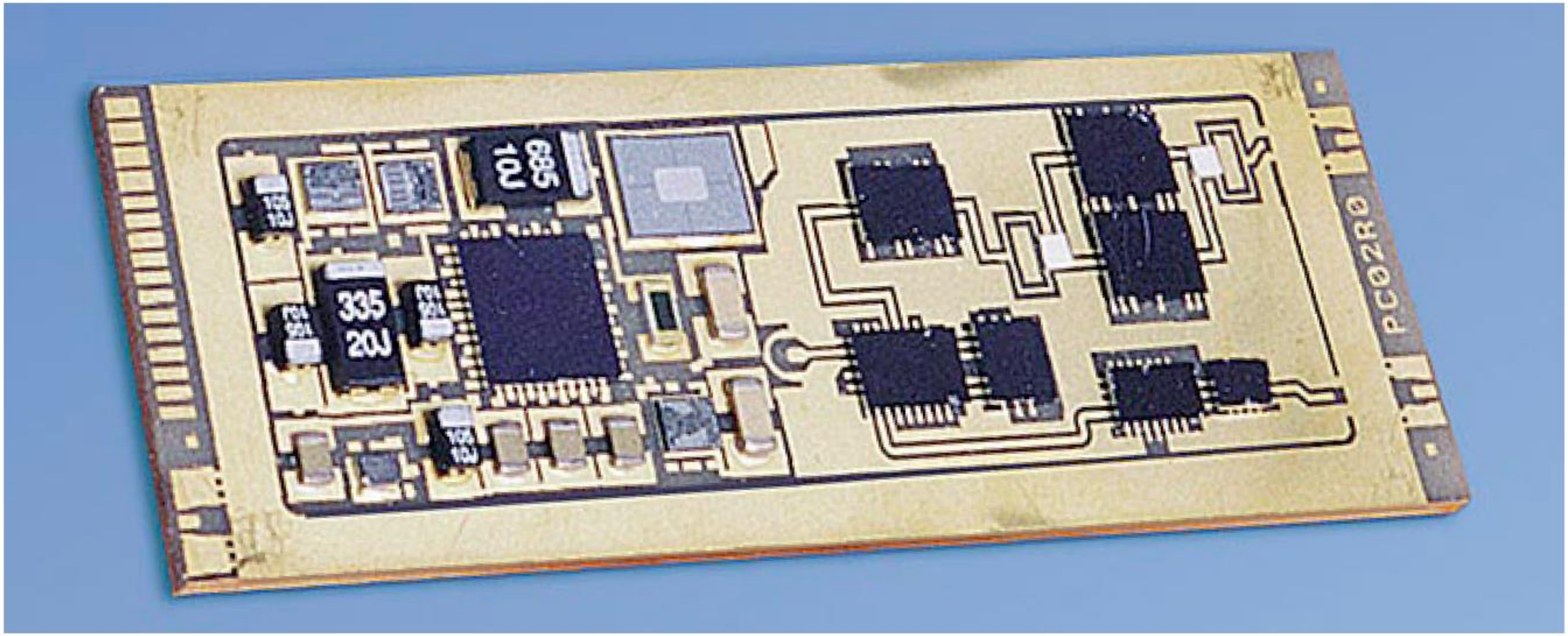
POSTECH

AESA

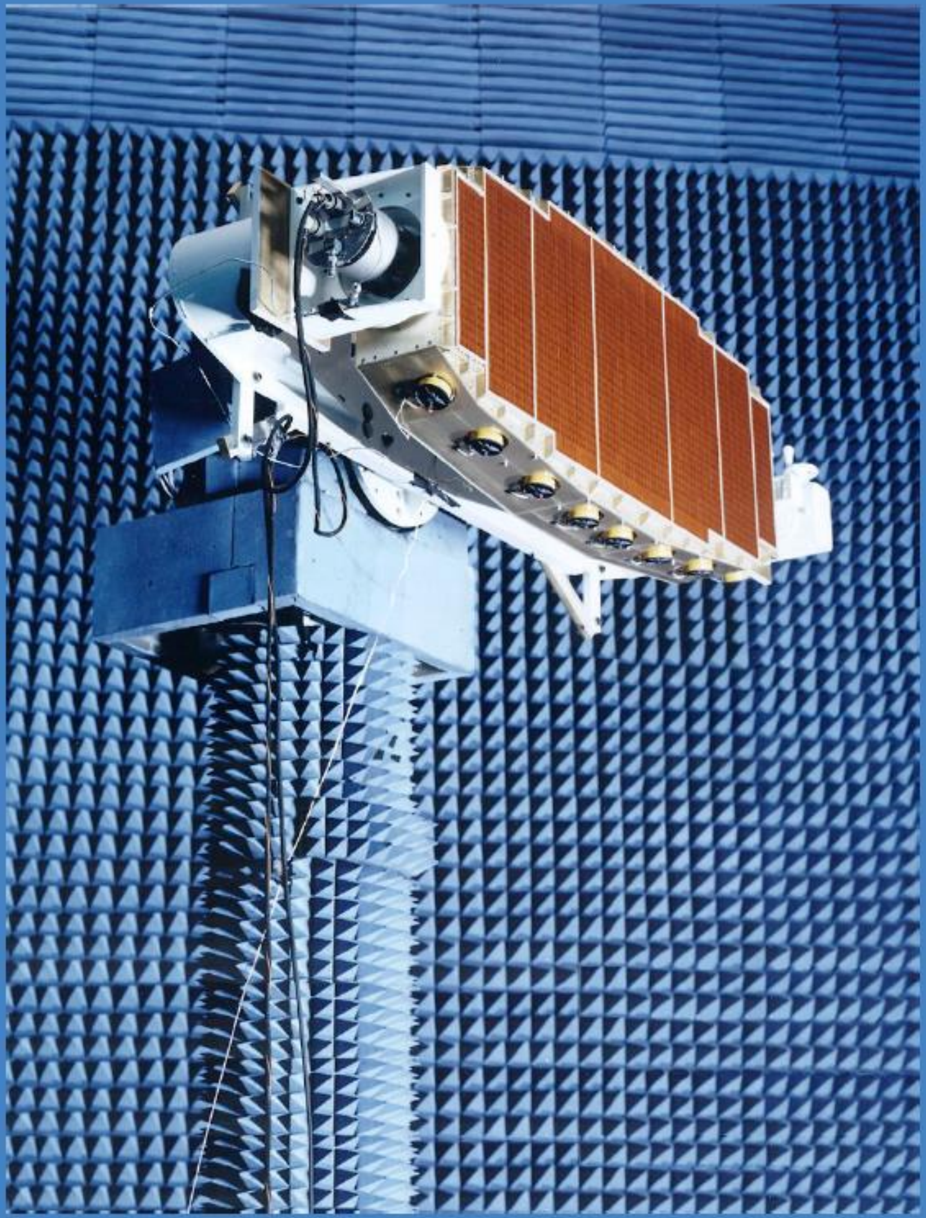


A representative T/R module. Even a fairly small ESA would include two to three thousand such modules.

T/R Modules



9. Closeup of a representative T/R module (cover removed). Integrated circuit chips are interconnected in a hybrid microcircuit.



SAR INDOOR TESTING

Passive ESA of the ultrahigh-resolution SAR radar for the U-2 reconnaissance aircraft undergoes tests in an indoor range.

POSTE

True Time Delay

- TTD ESAs are electronically steered arrays where phase shifts for beam steering are obtained by varying the physical lengths of the feeds for the individual T/R modules.
- Generally, a fiber-optic feed is provided for each module.
- The time delay experienced by the signals in passing through the feed—hence their phase—is controlled by switching precisely cut lengths of fiber into or out of the feed.
- Advantages:
  - Avoid the BW limitations that are inherent in electronic phase shifting.
  - This way, extremely wide instantaneous bandwidths can be achieved for arrays.

- The receiver and transmitter are located immediately behind the radiators. This essentially eliminates the effect of losses both in the antenna feed system and the phase shifters.
- In AESA, the net receiver noise figure is established by the LNA. It can be designed to have a very low noise figure.
- Comparatively in PESA it is established by losses in the phase shifter and feed network.
- Loss of transmit power is similarly reduced.
  - In PESAs, very high power and high efficiency TWTs are used. So this one might not be as bad.
- Control over the amplitude and the phase of individual radiators in both transmit and receive.
  - This provides a superior beam-shape agility.
- Multiple beam operation. Divide the aperture into several sub apertures & provide appropriate feeds.
- Through suitable T/R module design, independently steerable beams of widely different frequencies may simultaneously share the entire array.

More about Phased Arrays

- Electronic beam scanning techniques can be divided into four different categories:
  - Phase scanning.
  - Real time scanning.
  - Frequency scanning.
  - Electronic feed switching.
- We will give examples of these in the next few slides. The figures are borrowed from the following books:
  - Phased Array Antenna Handbook by R. Mailloux, Artech House, 2005, 2nd Edition, Norwood, MA.
  - Practical Phased Array Antenna Systems by Eli Brookner, 1991, Artech House, Illustrated Edition.

Phase Scanning

- This is similar to what we already discussed. The AESA and PESA architectures that we showed were both examples of this type of beam scanning array.

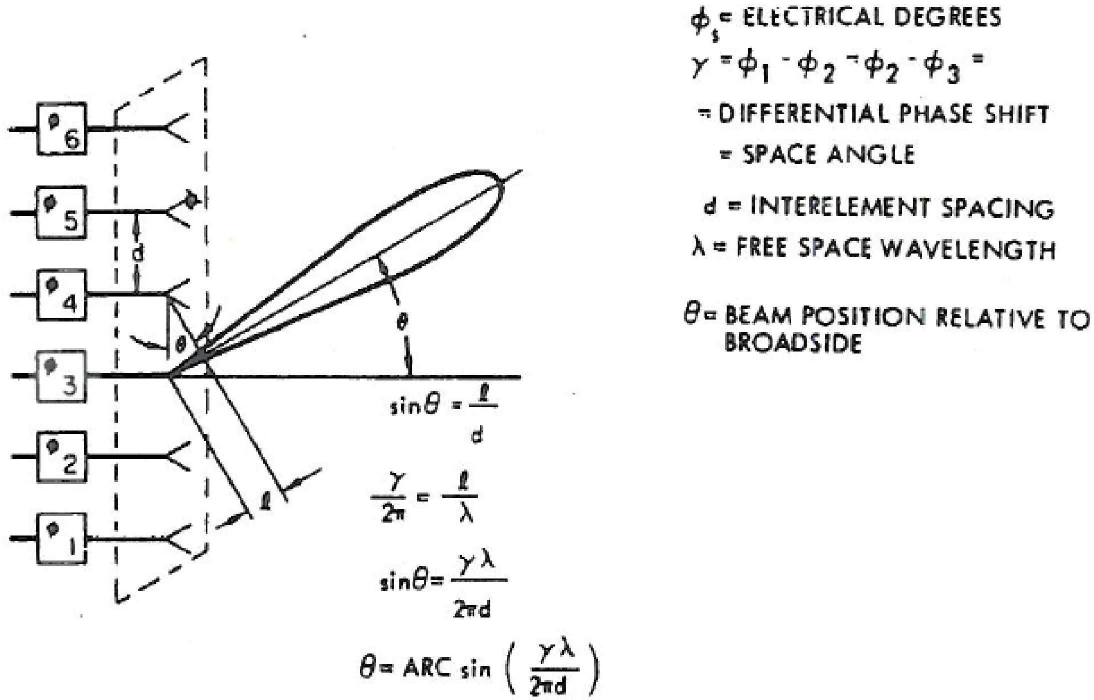


Fig 1-2. Basic operation of a phase scanning system. Note that beam direction depends on phase shift between elements

Continuous Phase Scanning

- Continuous phase scanning is accomplished by exciting all radiating elements coherently with a small frequency increment between them.
- The beam is continuously scanned at the rate of f.
- Think about it this way,
  - $\cos(\omega_0 t + \beta) = \cos([\omega_0 + \Delta\omega]t)$ ➔ $\beta = \Delta\omega t$.
  - The array is excited with a progressive phase of $\Delta\omega t$. This changes with time and consequently, the beam's direction changes with time.

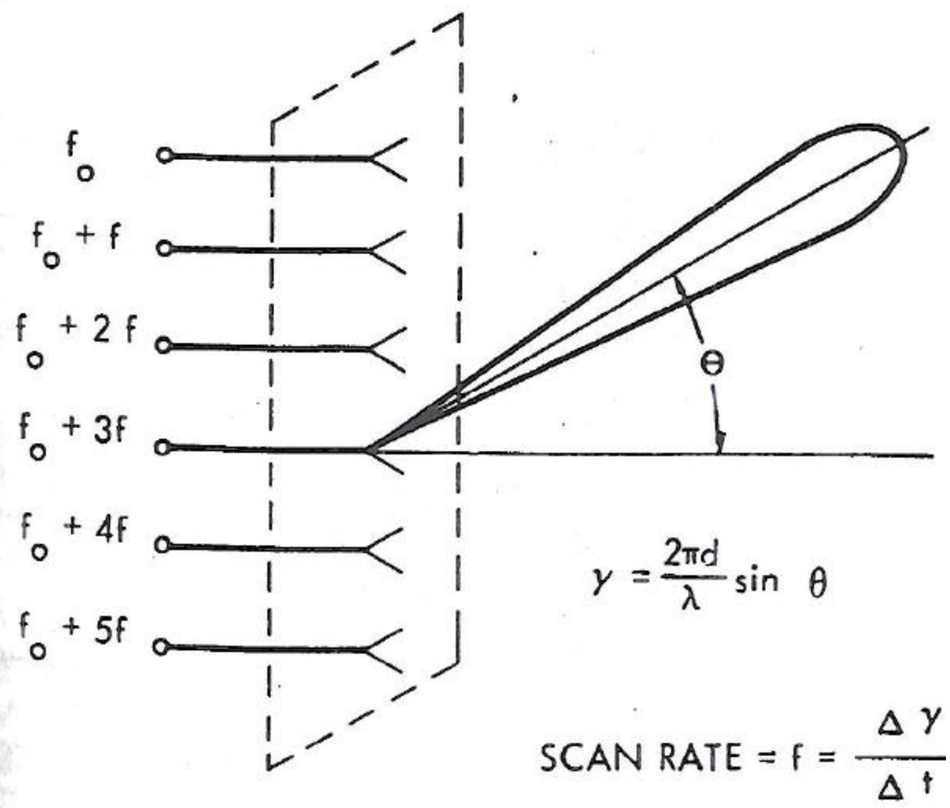
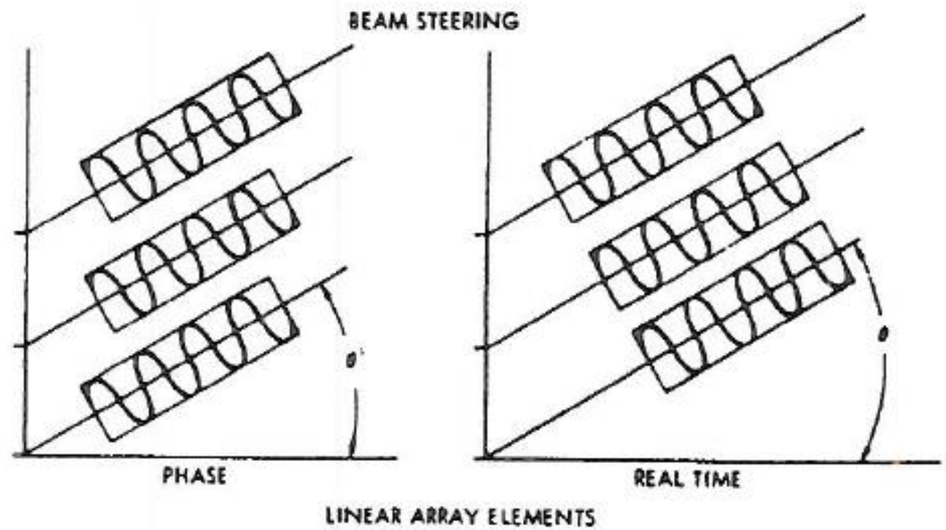


Fig 1-3 Continuous phase scanning

POSTECH

True Time Delay Beam Scanning

- TTD is necessary in beam scanning systems using wideband signals.



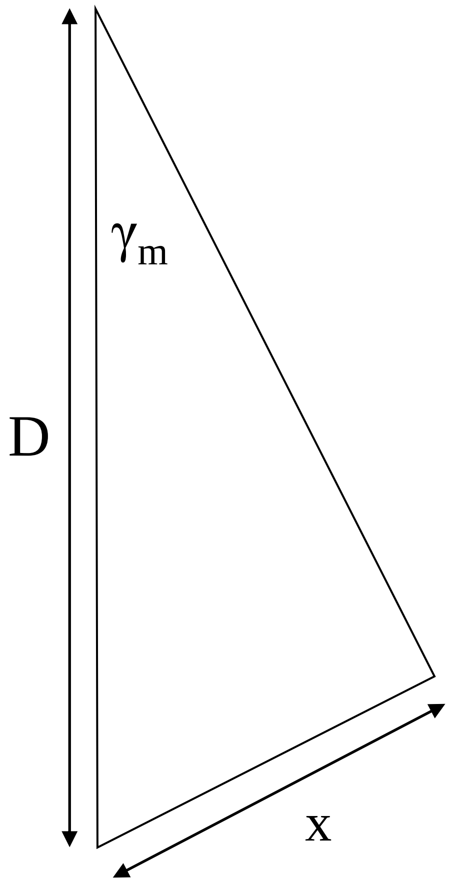
PHASE DELAY- THE PHASE OF SUCCESSIVE RADIATORS IS DELAYED TO OBTAIN PHASE (BUT NOT TIME) COHERENCY IN WAVEFRONT AT AN ANGLE θ FROM BROADSIDE.

TIME DELAY - THE TIME OF SUCCESSIVE RADIATORS IS DELAYED TO OBTAIN BOTH PHASE AND TIME COHERENCY IN WAVEFRONT AT AN ANGLE θ FROM BROADSIDE.

Fig 1-4 Comparison of phase and real time scanning

Bandwidth of Phase Scanning Systems

- X: Space length of travel of field from the last aperture element relative to first element to form wavefront at maximum scan angle γ_m.
- D=Length of array aperture.
- Time for signal to travel through the length x is $t = x/c = D\ \sin\gamma_m/c$, where $c = 3 \times 10^8$ m/s.
- $c = f/\lambda$ and $\theta_{3dB} \approx 64\lambda/D$ (θ_{3dB} is the 3dB beamwidth of the array).
- $t = 64\ \sin\gamma_m/(\theta_{3dB}\,f)$.

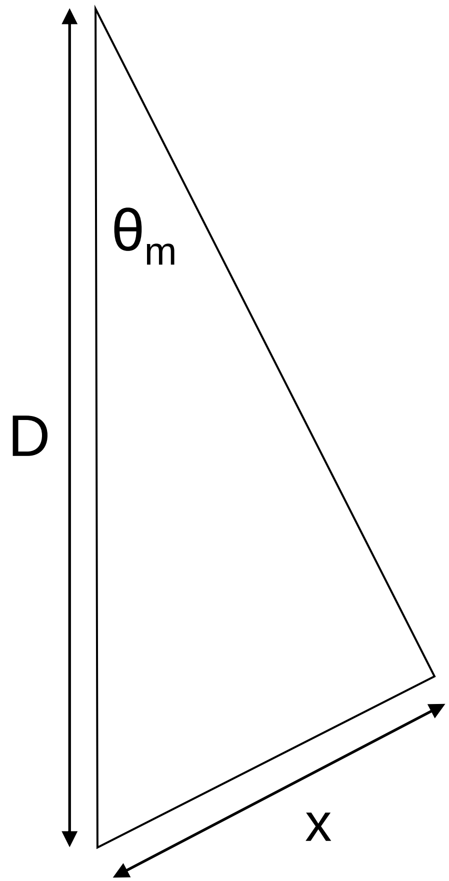


POSTECH

Bandwidth of Phase Scanning Systems

- Practical designs allow for a minimum of $\frac{1}{2}$ pulse width overlap between transmission from first and last radiating elements. Therefore, $t \leq \tau/2$, where τ is the pulse width.
- This way, $\tau \geq 128 \sin\theta_m/(\beta f)$.
- The Bandwidth (BW) of the signal is inversely proportional to $1/\tau$.
- Therefore:

$$BW \leq \frac{\theta_{3dB} f}{128 \sin \gamma_m}$$



POSTECH

Example

- Assume a $HPBW = 1°$, $f\ = \ 3$ GHz, and maximum scan angle = 60 degrees.
- This way, the maximum signal bandwidth that can be used with phase scanning systems is approximately 27 MHz.
- If this is not enough, then TTD systems must be used or a combination of TTD and Phase Shift system.

Frequency Scanning Arrays

- In a frequency scanning array, frequency is employed to control the inter-element differential phase shift so that each frequency corresponds to a unique beam position.
- This is a completely passive method and reciprocal.

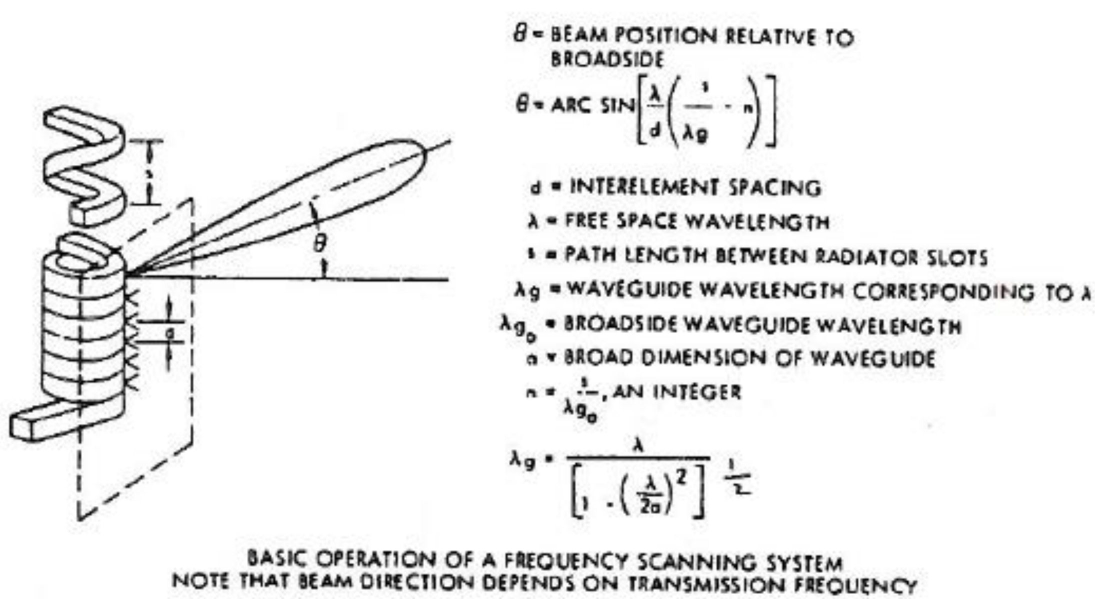


Fig 1-5 Basic operation of a frequency scanning system. Note that beam direction depends on transmission frequency

POSTECH

Frequency Scanning Arrays: Bandwidth Limitation

- Practical FS arrays employ an approximately 6% bandwidth to scan 90°.
- BW is limited by: (for derivation, refer to E. Brookner, Practical phased array antenna systems)

$$BW \leq \frac{\theta_{3dB} \Delta f}{256 \sin \gamma_m}$$

- γ_m is the maximum scan angle measured from the plane of the array.
- e.g. for $\theta_{3dB} = 1°$, $f = 3$ GHz, $\Delta f = 180$ MHz, and $\gamma_m = 60°$ the maximum signal bandwidth that can be used is 0.8 MHz.

Electronic Feed Switching: Hybrid/Butler Matrix

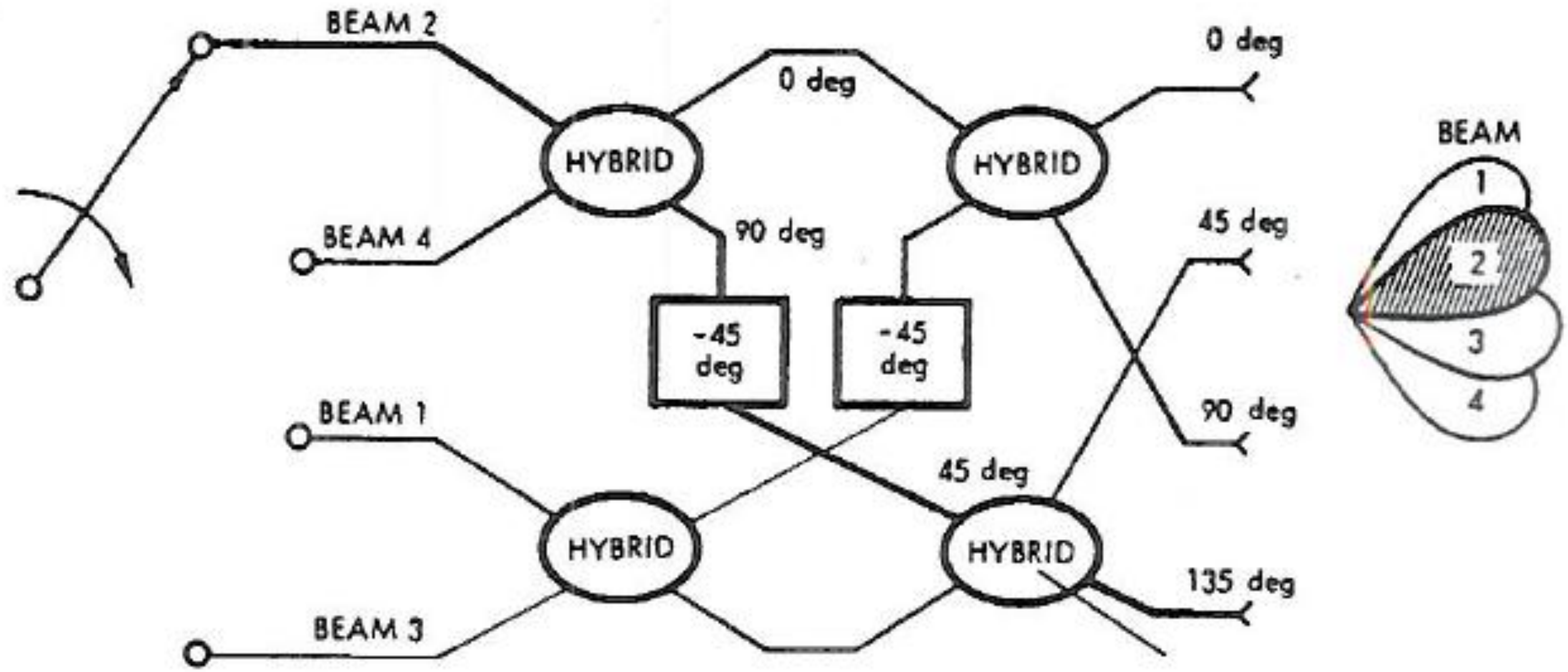


Fig 1-6 Hybrid/Butler matrix
Basic operation of an electronic feed switching system

Electronic Feed Switching: Luneburg Lens

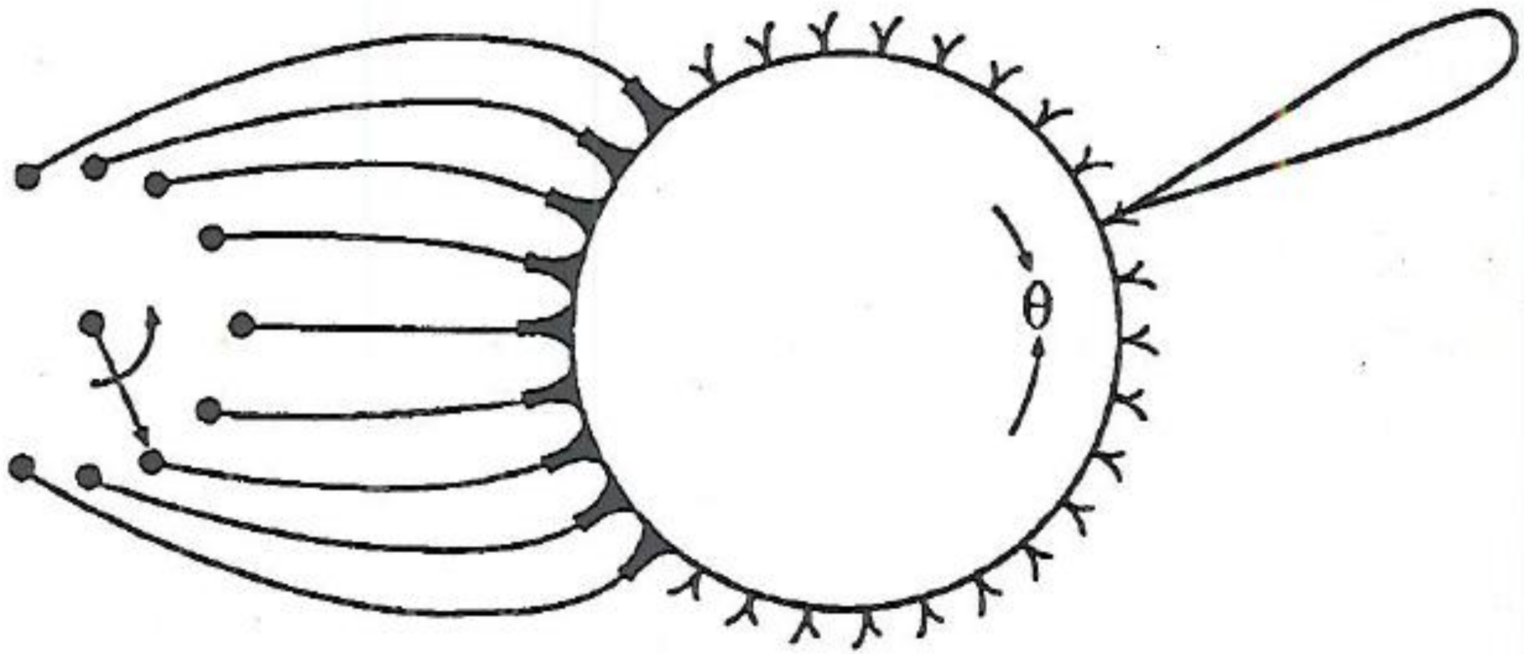


Fig 1-7 Luneburg Lens
Basic operation of an alternative electronic feed switching system

Electronic Feed Switching

- EFS Systems can be wideband or narrow band.
- The two examples shown, the Butler matrix approach’s bandwidth is limited to the hybrid circuits’ and phase shifters’ bandwidths used.
- The Luneburg lens is a wideband approach for beam steering.
- Other lens types can be used including Rotman lens:
  - Bandwidths will be different based on the approach used. For example Rotman lens is generally a wideband approach whereas other lenses may or may not be wideband based on specific design of lens.

N Element Linear Array: Directivity

- Procedure:
  - The procedure for calculating directivity of the array factor is straight forward.
  - The array factor is essentially our radiation pattern function.
  - Calculate the total radiated power + Radiation Intensity, etc.
- Broadside Array:

$$D_0 = 2N\left(\frac{d}{\lambda}\right)$$

- Ordinary End Fire Array:

$$D_0 = 4N\left(\frac{d}{\lambda}\right)$$

- Hansen-Woodyard:

$$D_0 = 1.805 \times 4N\left(\frac{d}{\lambda}\right)$$

POSTECH

Example: Problem 6.18 of text

- An array of 10 isotropic radiators are placed along the z-axis a distance d apart. Assuming uniform distribution, find the progressive phase (in degrees), half-power beamwidth (in degrees) first null beamwidth (in degrees), first side lobe level maximum beam width, relative side lobe level maximum (in dB), and directivity in dB
  - Broadside
  - Hansen Woodyard End Fire
  - Ordinary End Fire
- Assume $d=\lambda/4$

POSTECH