- 2023-08-23
- 양성준, 서울과학기술대학교
- 하계종합학술대회 워크숍

Microwave cavities and modes for material heating

Outline

01 Introduction: cavity and mode

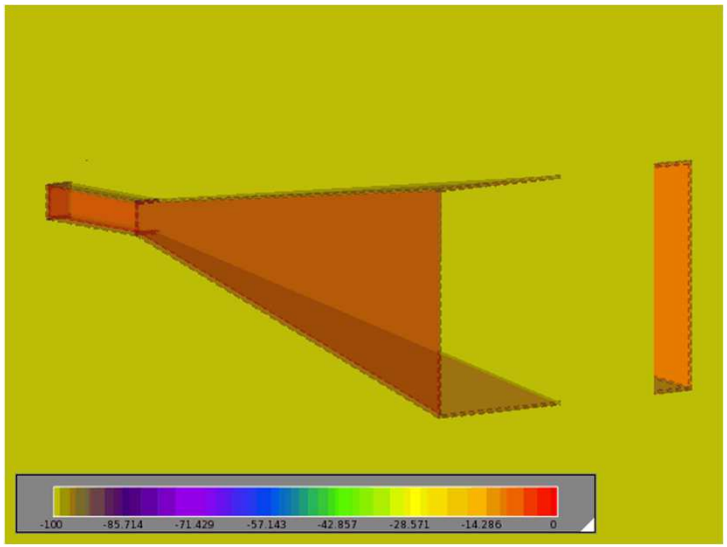
02 Single-mode cavities

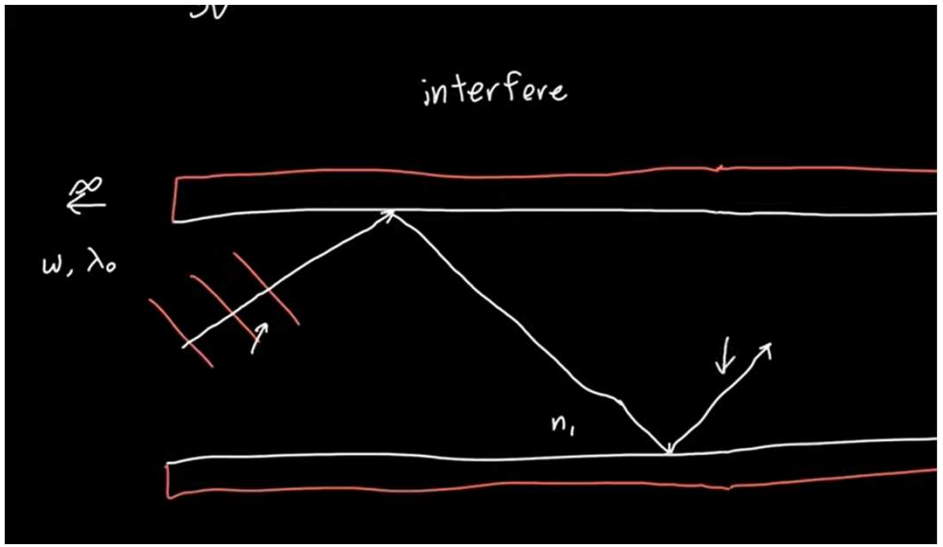
03 Multi-mode cavities

Introduction: cavity and mode

Modes

- waveguide에서 EM wave의 진행 방향은?
- EM wave의 multi-superposition
- vector decomposition (figure)

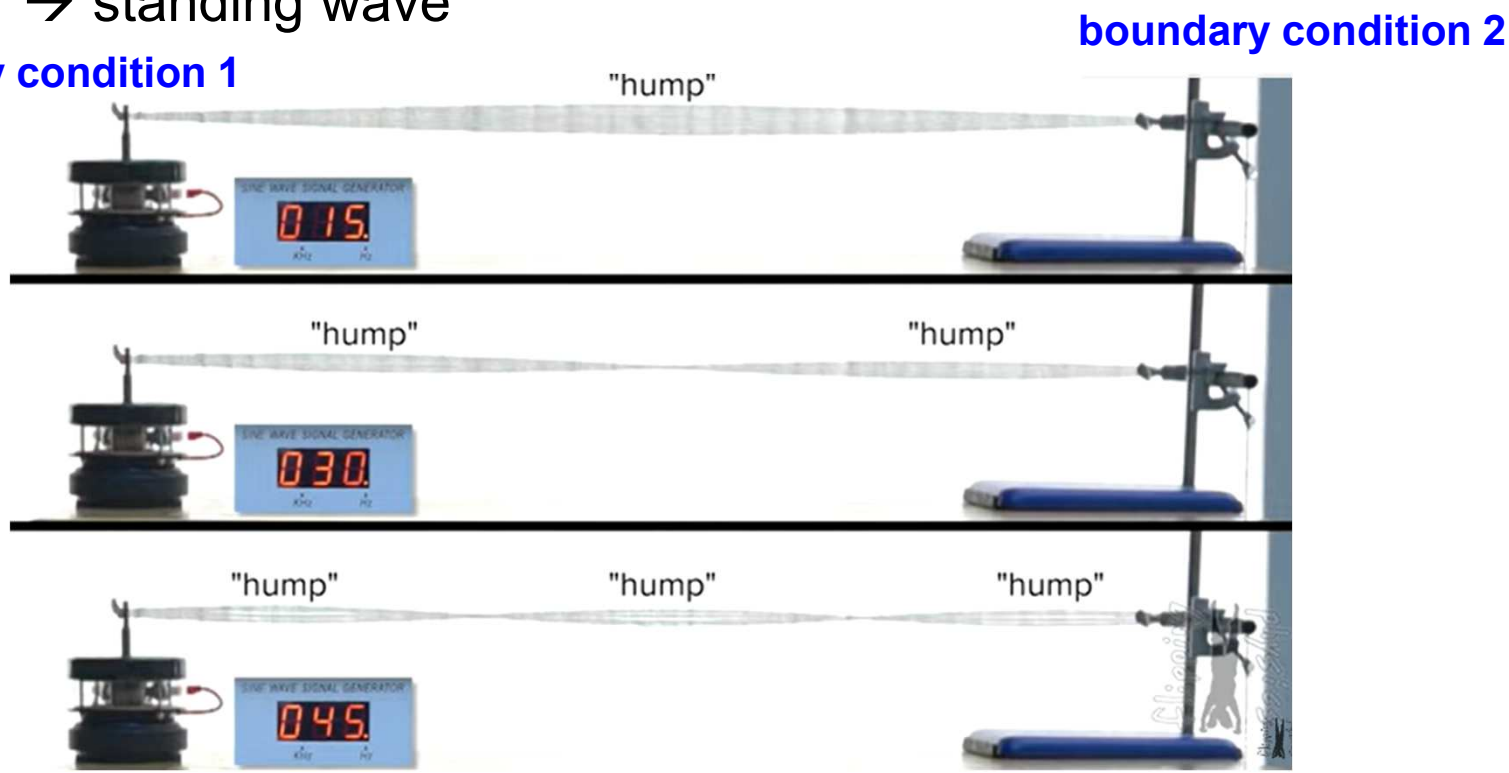




Introduction: cavity and mode

Modes

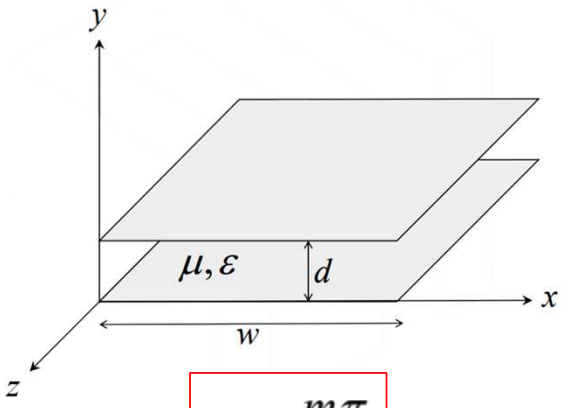
- standing waves of EM fields
- reflection 발생 → standing wave



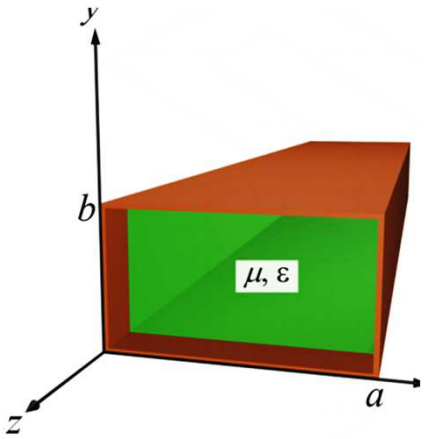
Introduction: cavity and mode

Modes

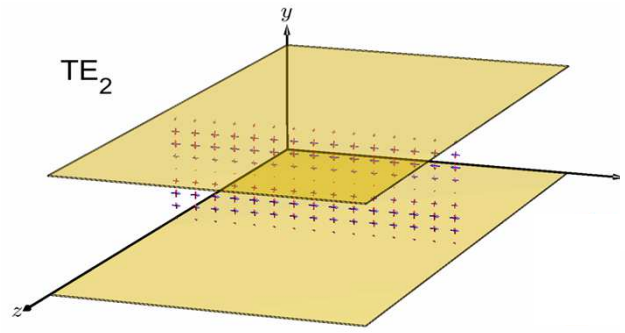
- 1-D mode
  - two parallel plate
  - TE_1, TM_2, …
- 2-D mode
  - rectangular waveguide
  - TE_{12}, TM_{33}, …

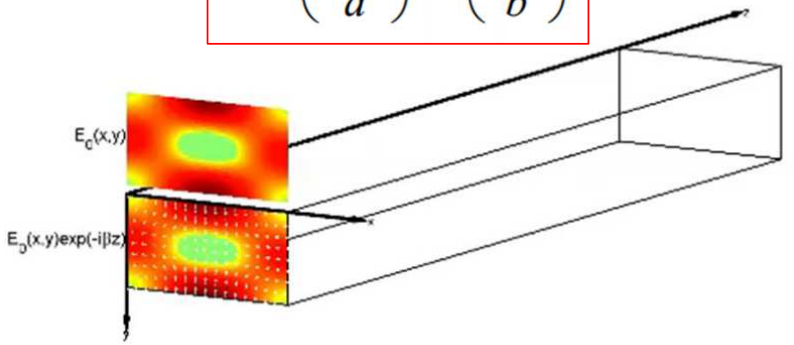


$$k_c = \frac{m\pi}{d}$$



$$k_c^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2$$

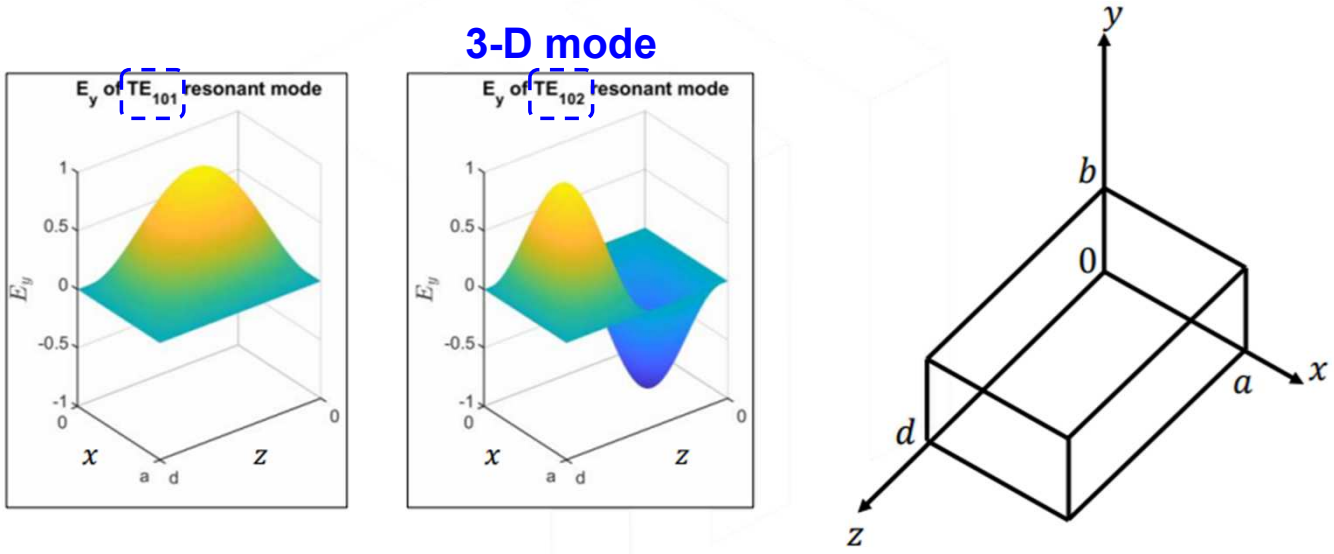




Introduction: cavity and mode

Modes

- 3-D mode
  - cavity
  - TE_{ijk} / TM_{ijk}
- multiple combinations of 3-D resonance (e.g. x, y, z)

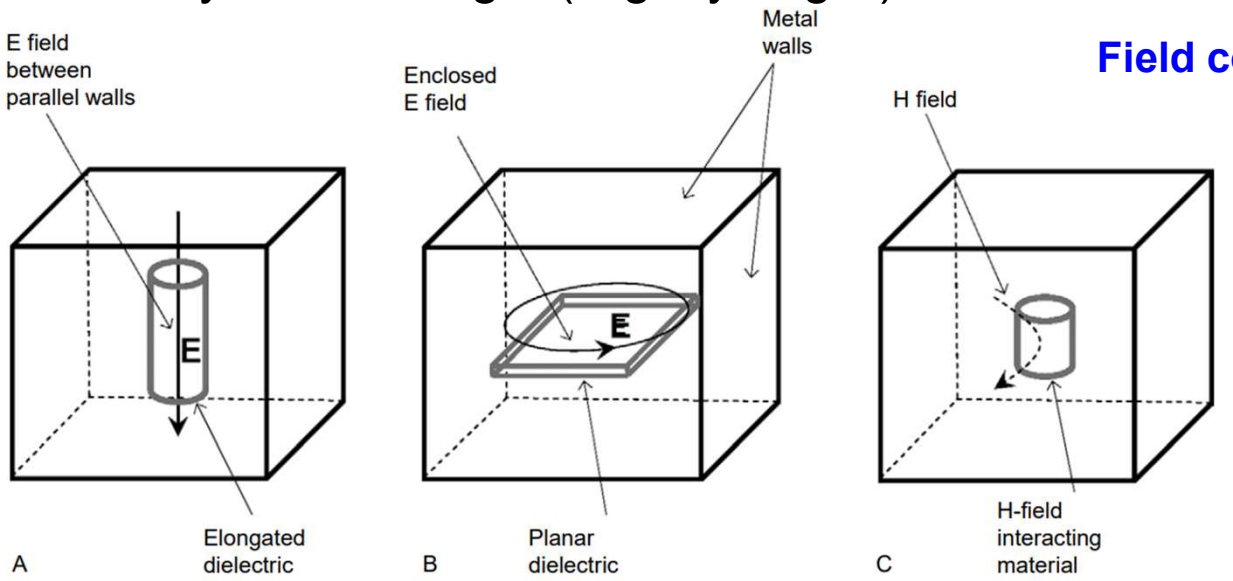


Single-mode cavities

What single-mode means:

- only one mode (only one combination is available)
  - **design parameter 1.** boundary conditions: dimension and shape of cavity
  - **design parameter 2.** wavelength of EM source
  - **design parameter 3.** coupling structures

  → dimension of cavity > wavelength (slightly larger)



Field configurations of TE_{101}

Single-mode cavities

FEM*: Finite Element Method
FDTD**: Finite-Difference Time-Domain

Properties of single-mode

- fixed **field distribution**
- high **Q-factor** → high **sensitivity**
- can focus **E-field (intense field)**

- to predict field distribution,
- can solve **analytically** in simple cases (rectangular, cylindrical, etc.)
- can solve **numerically** in general cases → FEM*, FDTD**, multi-physics, etc.

Single-mode cavities

Properties of single-mode

- load:
  - ex) food, chemical, liquid, ceramic, metal, …
  - variable 1) dielectric properties
  - variable 2) dimensions and shapes

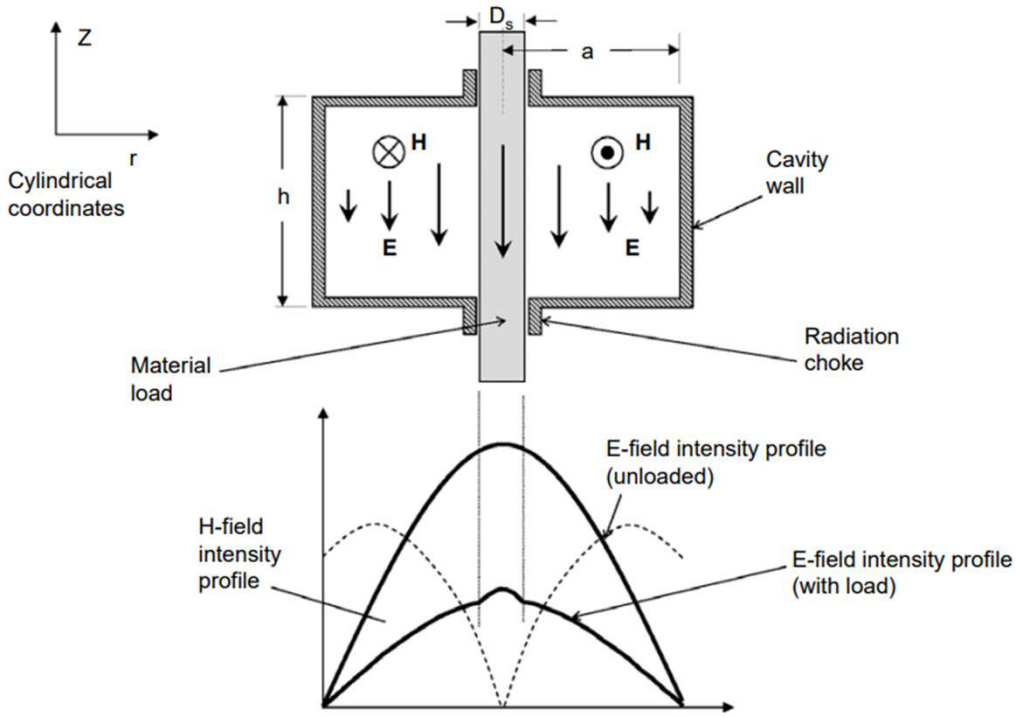
- effect of adding loads
  - modify field distribution and impedance in cavity
  - modify available modes

Single-mode cavities

loaded cavities

- addition of **dielectric load**
  - reduce intensity of field
  - reduce wavelength inside the material
  - reduce resonant frequency
    - → break impedance matching
    - → reflected power into magnetron
    - → cavity size should be reduced
  - reduce Q-factor
    - → increase bandwidth

higher dielectric → more flat field

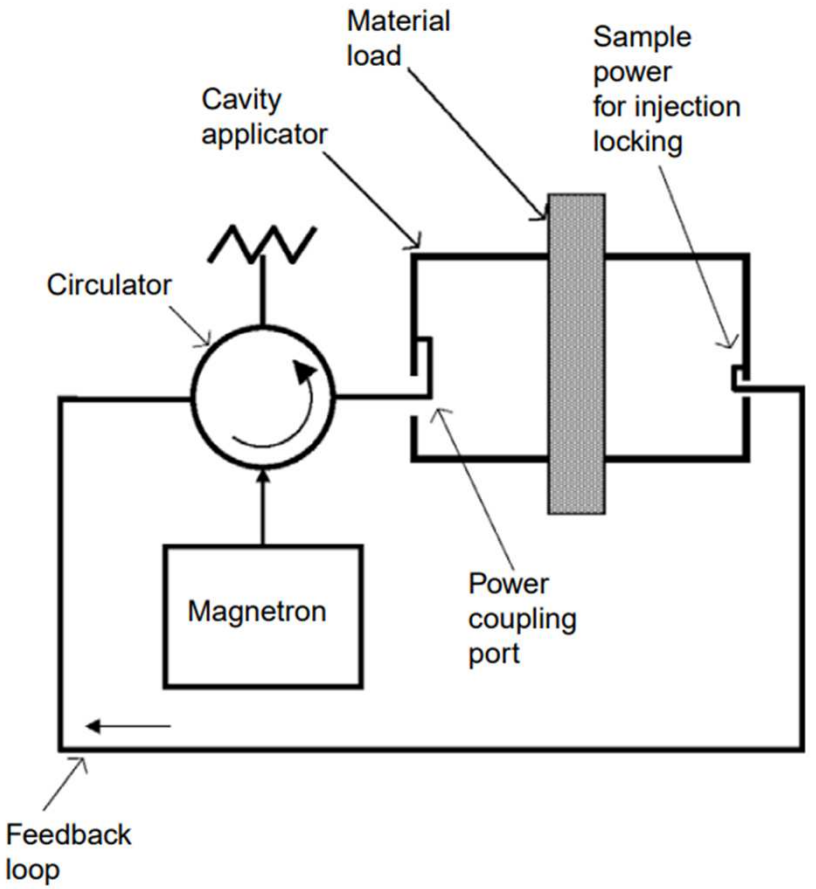


load 내부에서는 wavelength 감소
→ electrical dimension이 커진 것과 같음

Single-mode cavities

loaded cavities

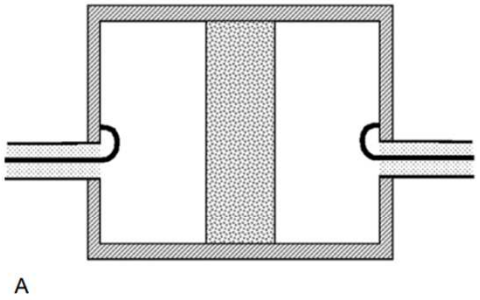
- addition of **dielectric load**
  - reduce intensity of field
  - reduce wavelength inside the material
  - reduce resonant frequency
    - → break impedance matching
    - → reflected power into magnetron
    - → cavity size should be reduced
  - reduce Q-factor
    - → increase bandwidth

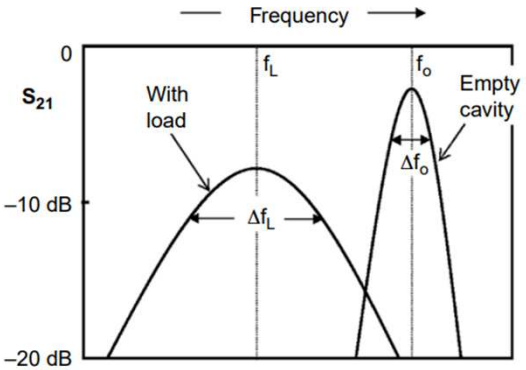


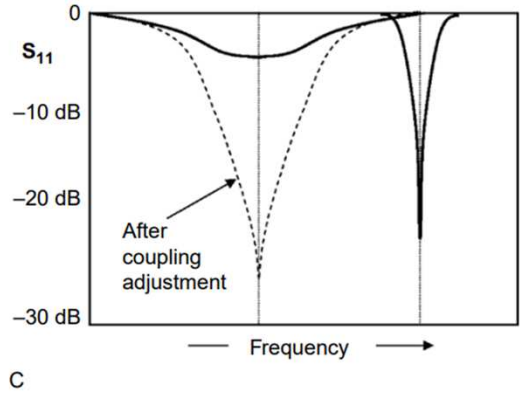
Single-mode cavities

loaded cavities

- addition of **dielectric load**
  - reduce intensity of field
  - reduce wavelength inside the material
  - reduce resonant frequency
    - → break impedance matching
    - → reflected power into magnetron
    - → cavity size should be reduced
  - reduce Q-factor
    - → increase bandwidth







SEOULTECH

CEMLAB

Single-mode cavities

Properties of single-mode

- high sensitivity
  - difficult to maintain the ‘single-mode’ condition
  - dielectric material sensors (w/ shift in resonant frequency or signal loss)
  - dielectric measurements (in a narrow frequency band) → two ports

- high E-fields
  - plasma activation
  - low-loss materials (ceramics)

Single-mode cavities

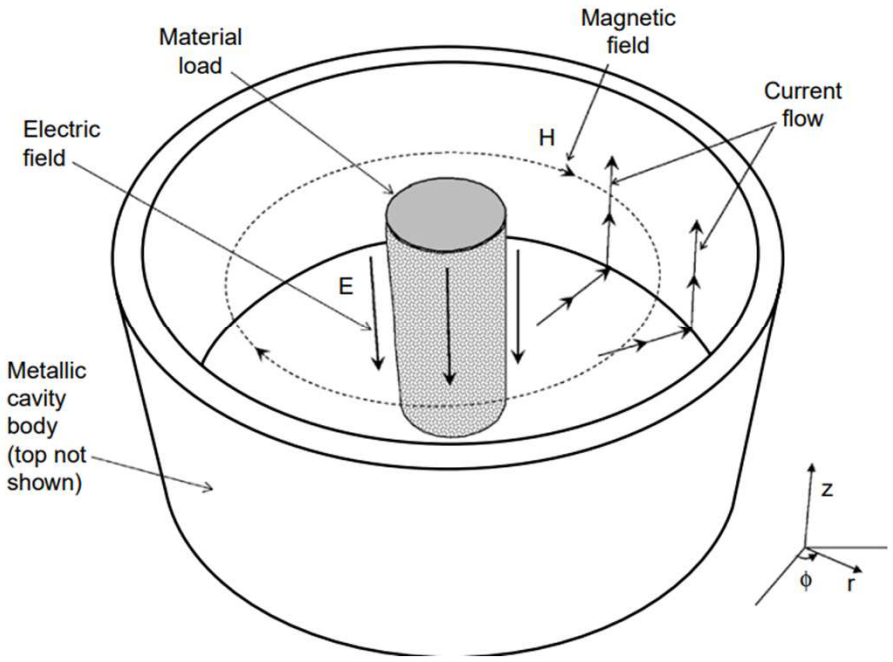
Properties of single-mode

- single-mode cavities need
  - stable loads
    - industrial processing (pumpable or conveyed materials)
  - small-sized loads
  - low-dielectric constant materials: quartz, ceramic
  - tunable cavity or feedback loop
  - **food**: not appropriate application (not specific geometry, high-dielectric loss)

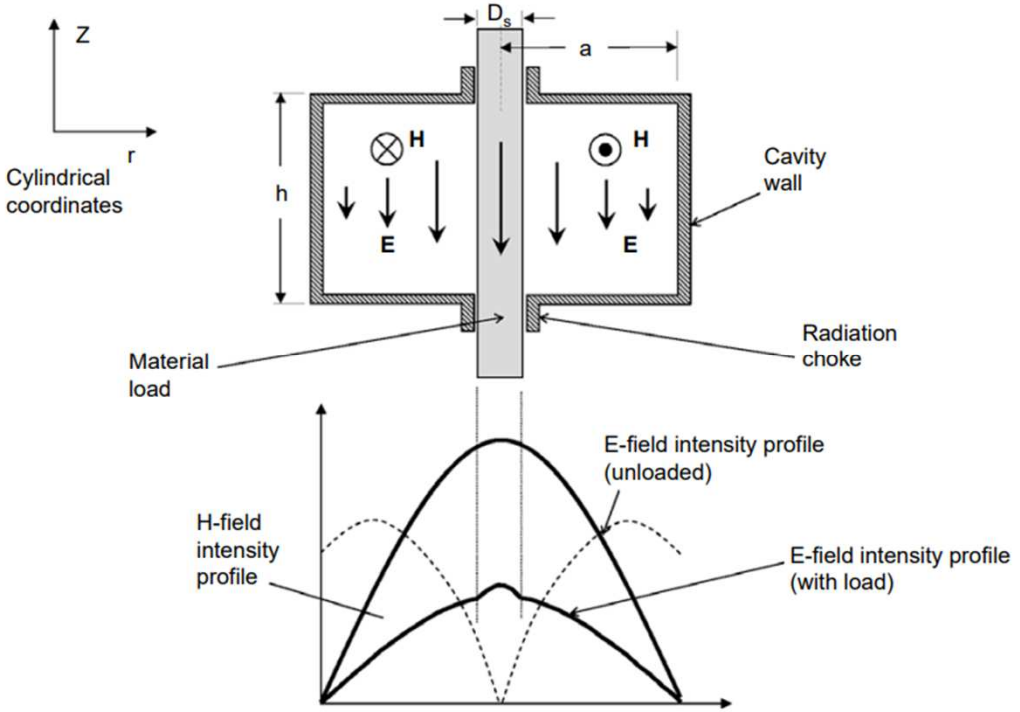
Single-mode cavities

Applications

- example) cylindrical TM_{010}



for 'unloaded' cavities,
can be derived analytically (using wave equations)



SEOULTECH

CEMLAB

Single-mode cavities

Design process

- to predict unknown parameters:
- geometrical parameters (physical dimensions)
- material properties
  - load material
  - supporting structures
  - cavity
- electrical parameters
  - resonant frequency
  - Q-factor
  - coupling parameters

Single-mode cavities

Design process

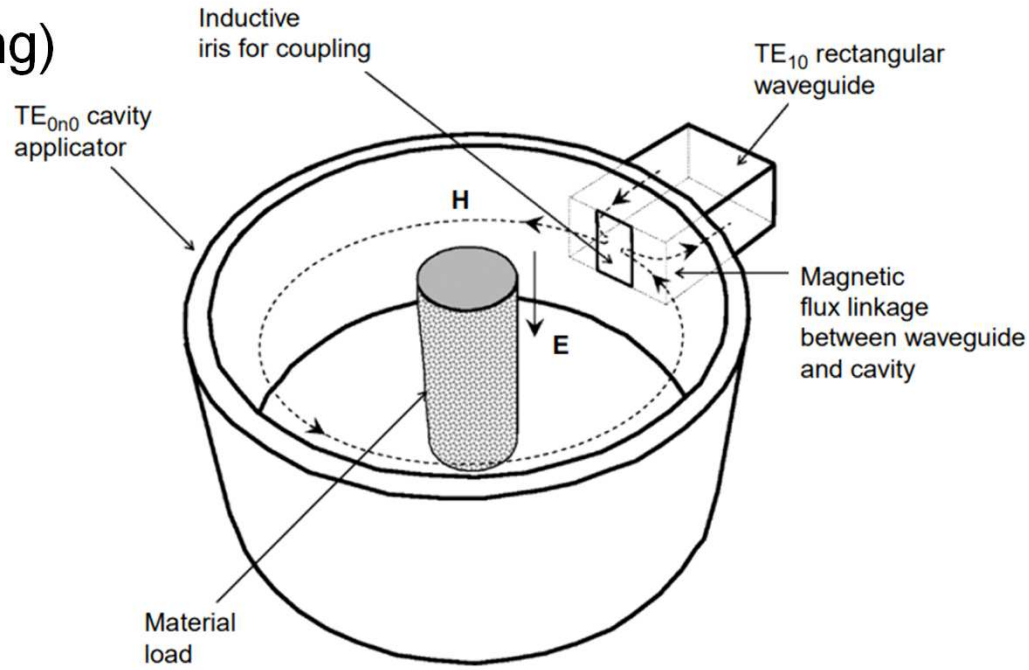
- dielectric properties of material?
- why you need single-mode cavity?
- desired frequency? sensitivity criteria?
- which mode? field configuration? place of material?
- dimension of cavity?
- coupling method?
- suppress other modes.

Single-mode cavities

iris*: opening at the physical junction

Coupling methods

- connect transmission line to cavity
- for impedance matching (critical coupling)
- 1) iris* coupling method
  - magnetic flux linkage
  - inductive iris
    - vertical to broad wall of waveguide
    - better breakdown capability
  - adjust width of iris
  - heavier loads → wider iris

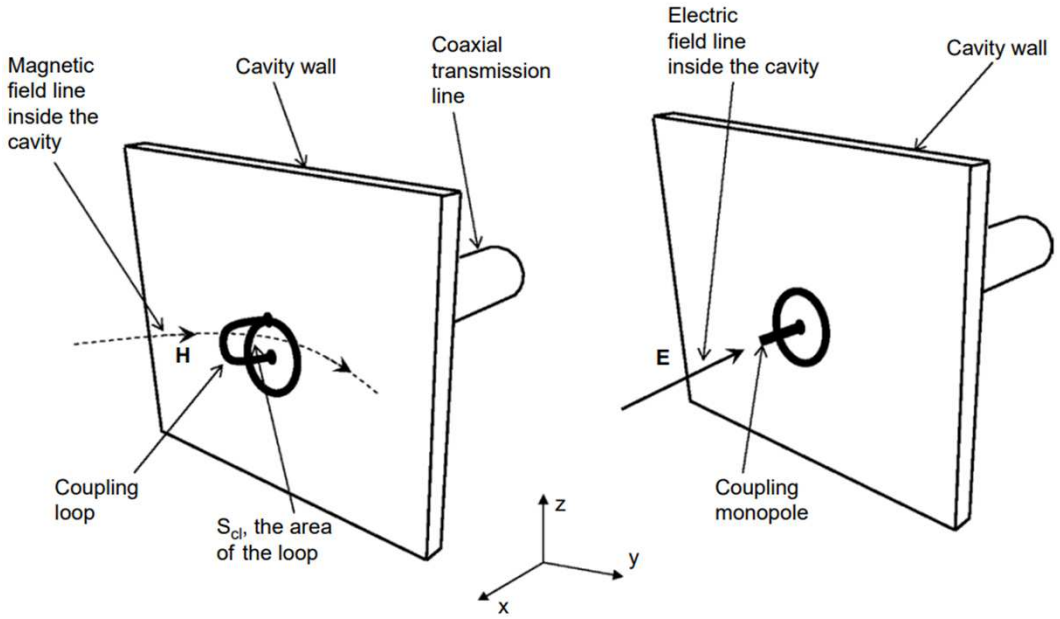


Single-mode cavities

Coupling methods

- 2) loop coupling method
  - magnetic flux linkage
  - adjust area of loop
  - heavier loads → wider loop

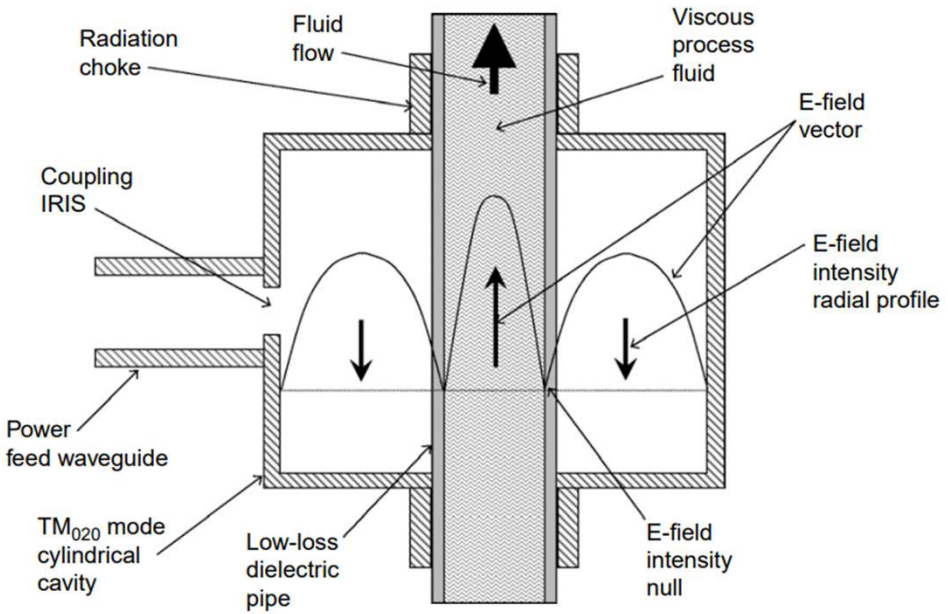
- 3) monopole antenna method
  - electric field coupling
  - adjust length of monopole



Single-mode cavities

Application examples

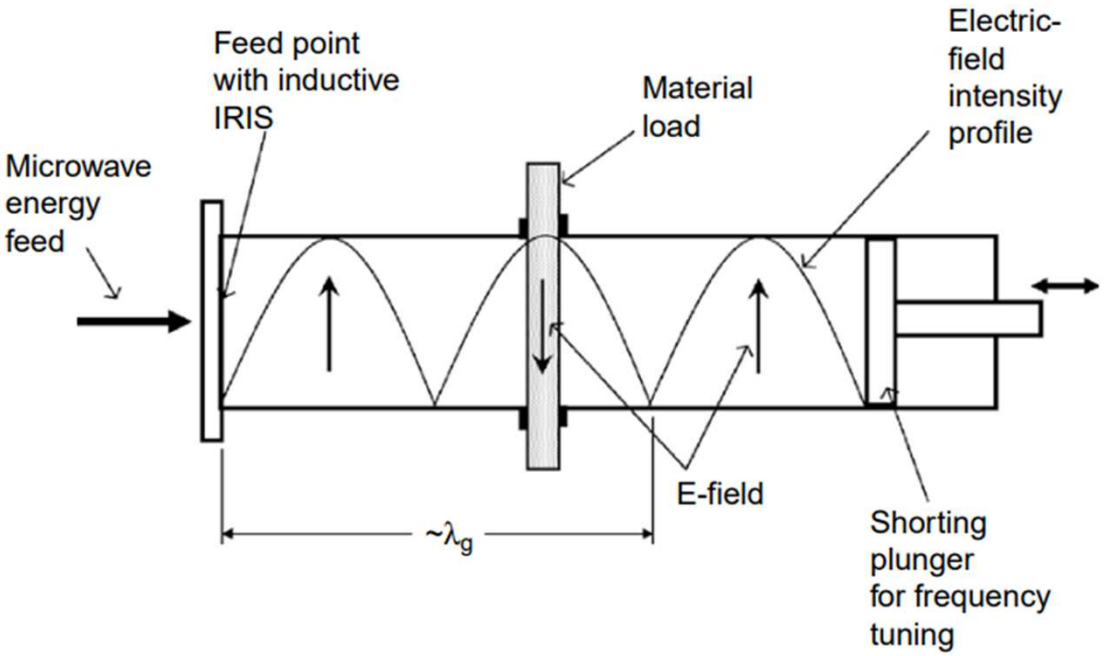
- heating flowing fluid
  - heating of adhesives for automobile interior assembly
  - convection heating at pipe
  - differential flow rate in pipe
  - use TM_{020} mode



Single-mode cavities

Application examples

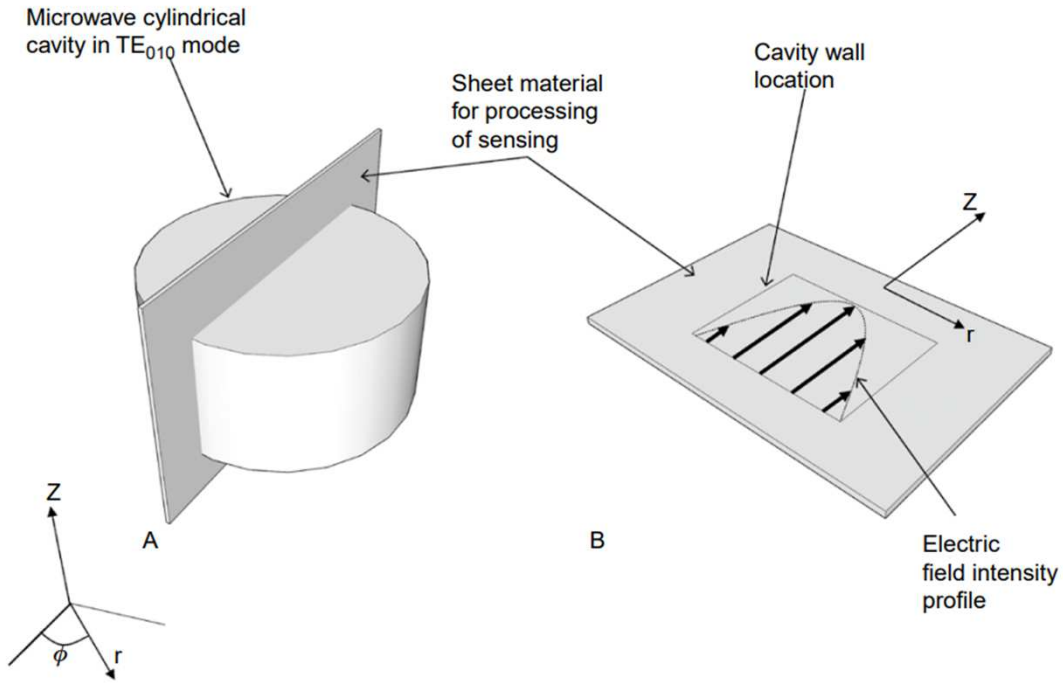
- cavity variation for frequency tuning
  - by adjusting side-wall, find a resonant dimension
  - load should be placed where maximum field



Single-mode cavities

Application examples

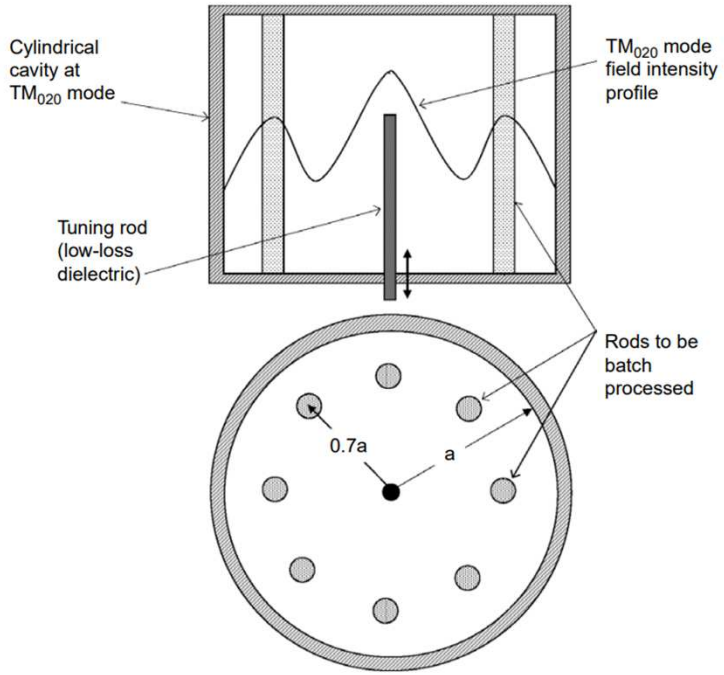
- heating or dielectric measurement of planar materials
  - using uniform field along z-direction

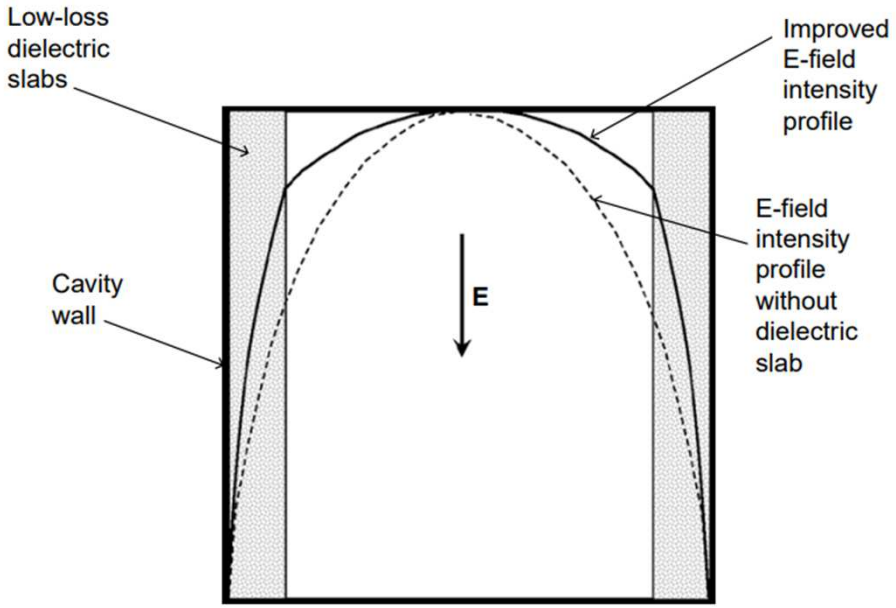


Single-mode cavities

Application examples

- modifying field configuration
  - using tuning rod
  - using dielectric slabs → improving E-field uniformity





Multi-mode cavities

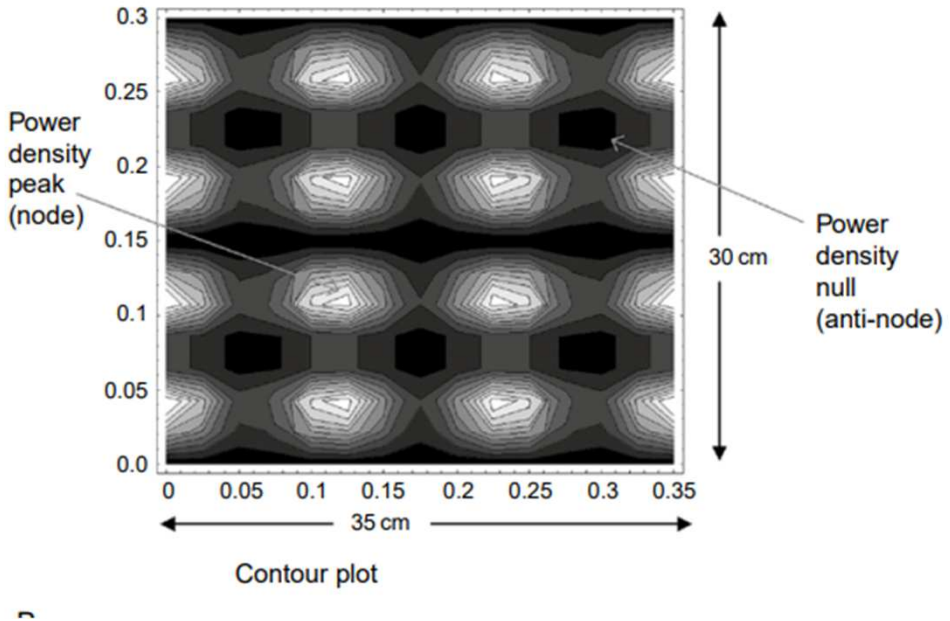
Introduction

- most commonly used (domestic microwave oven)
- robust and simple
- material heating & plasma activation
- microwave-enhance chemistry
- sintering of materials (ceramics)

Multi-mode cavities

Why multi-modes are needed?

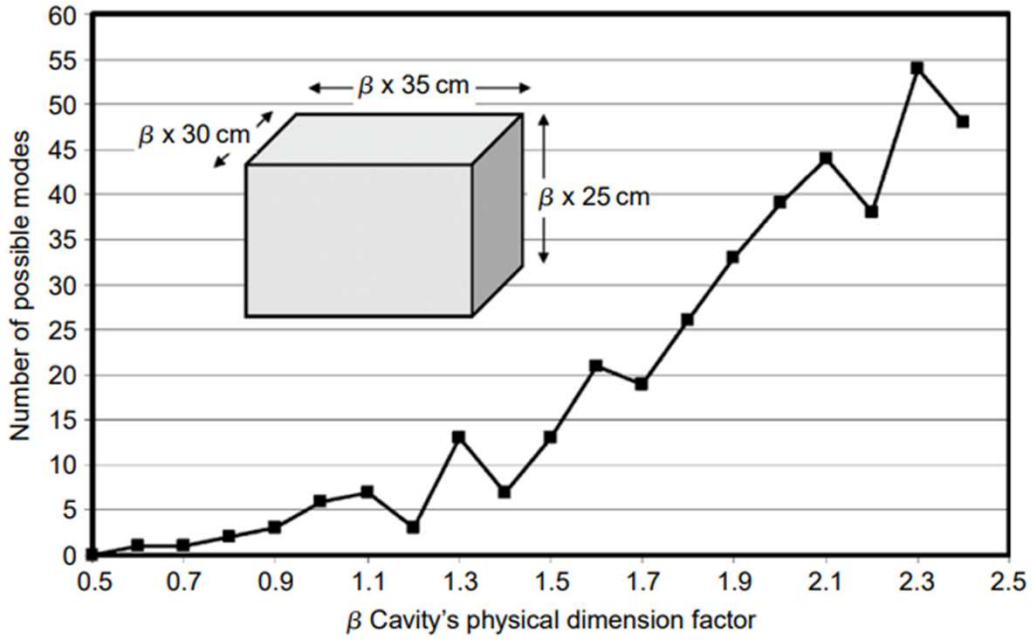
- poor field uniformity of each single-mode
- multi-mode = superposition of single-modes → reduce true field nulls
- the more modes, the better uniformity



Multi-mode cavities

Properties

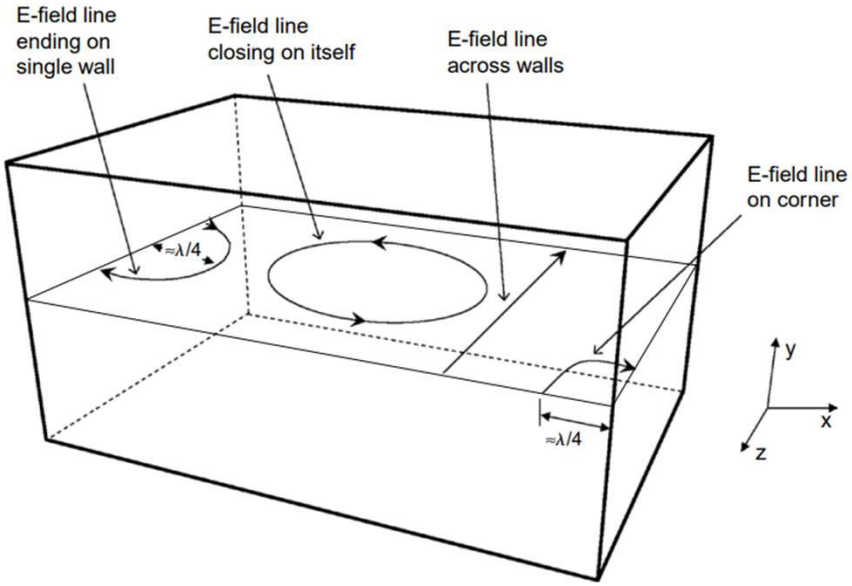
- **large cavity**: the larger cavity, the more modes

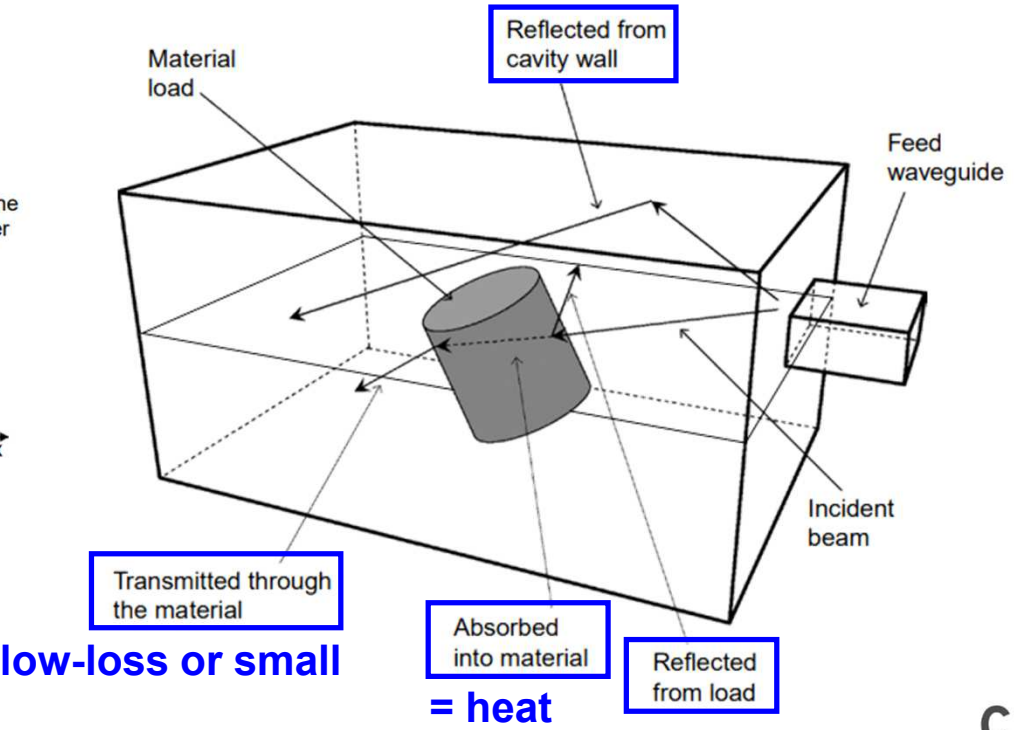


Multi-mode cavities

Properties

- difficult to predict field configuration
- use optical beam model (ray model)





low-loss or small

= heat

SEOULTECH

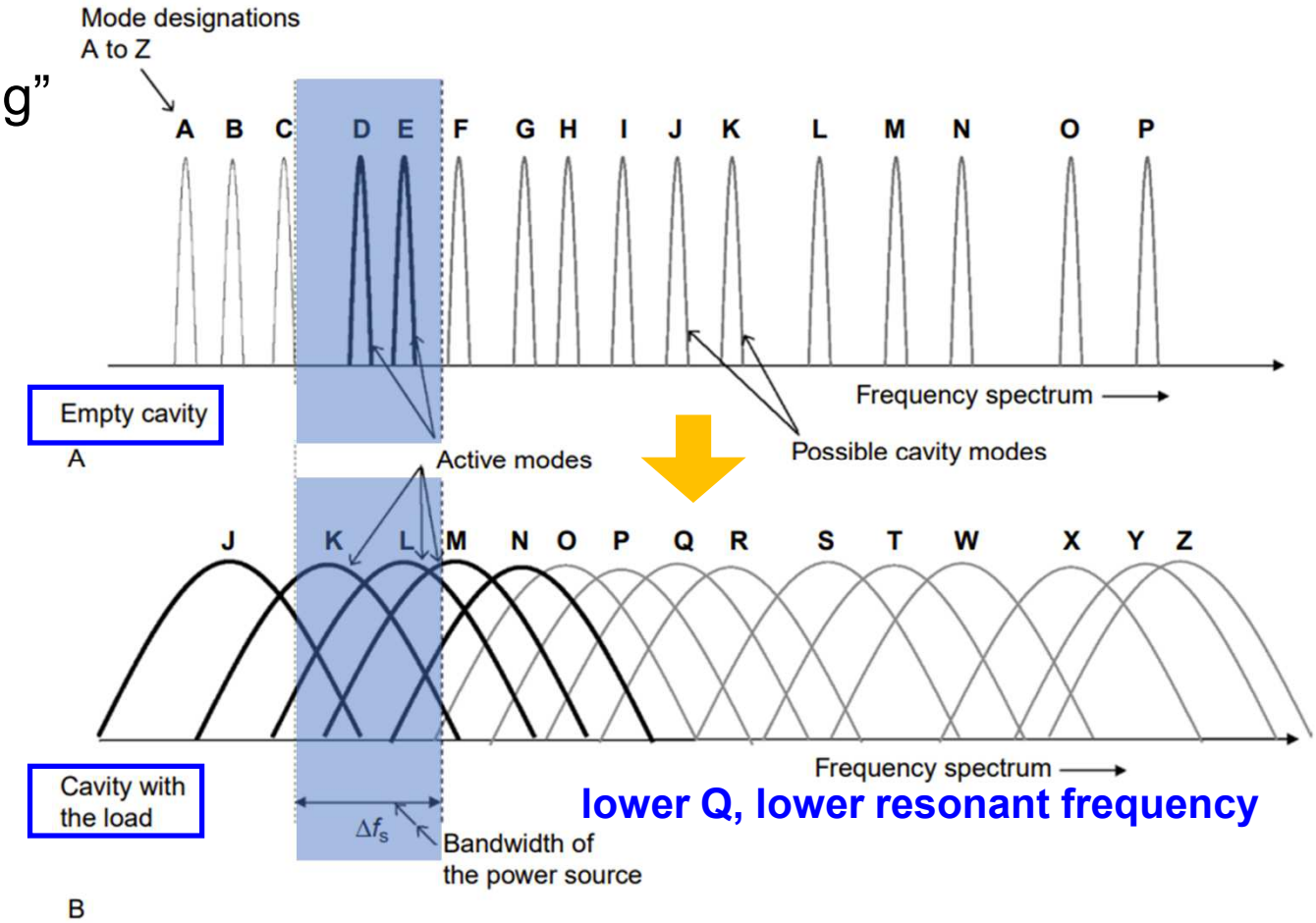
CEMLAB

Multi-mode cavities

Properties

- **robustness**: no need of “tuning”
- modes in frequency band
  - D, E (empty cavity)

  → J, K, L, M, N (with load)
- **low Q**: cannot ‘focus’ field
  - bad for low-loss materials



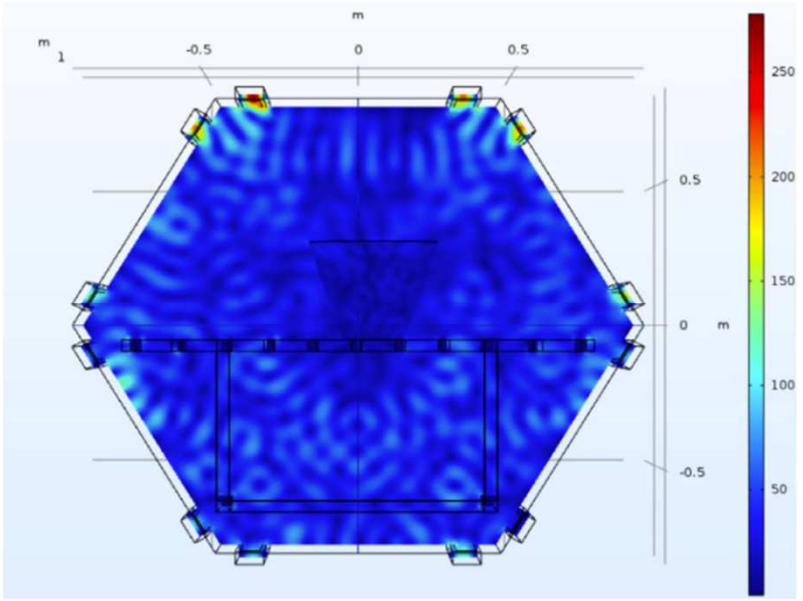
SEOULTECH

CEMLAB

Multi-mode cavities

Heating uniformity

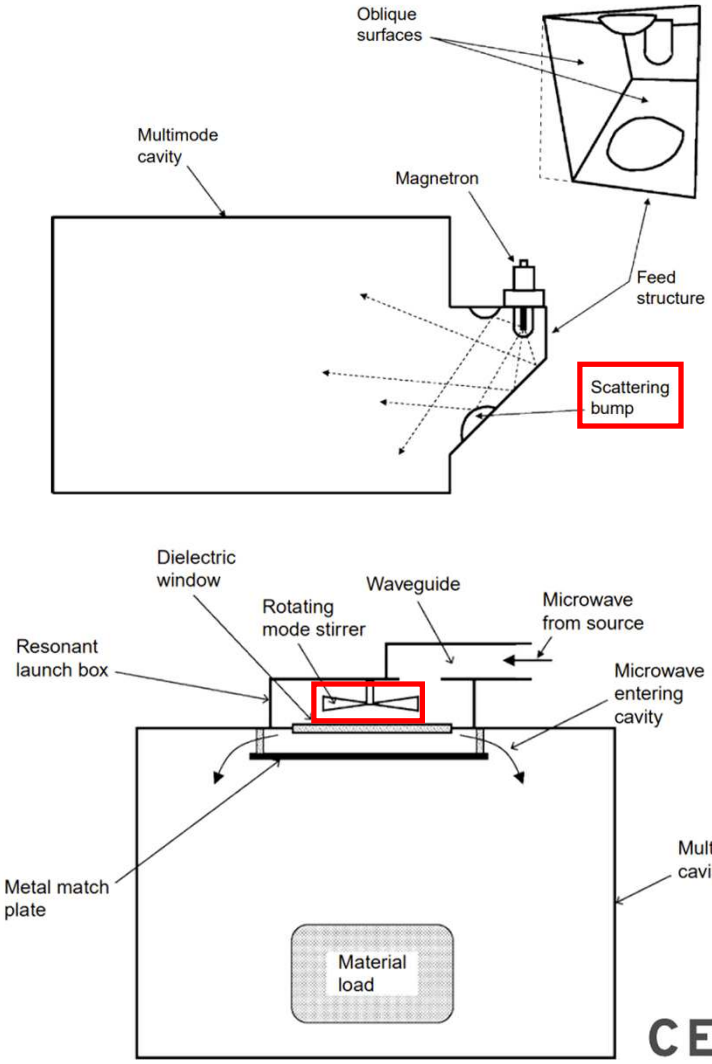
- spatial temperature variation
- **field uniformity**
  - larger cavity → more potential modes
  - complex geometry of cavity (curved or angular walls)
  - e.g. hexagonal cross-section



Multi-mode cavities

Heating uniformity

- spatial temperature variation
- **field uniformity**
  - *for more operating modes,*
  - use higher frequency (gyrotron source)
  - use frequency sweeping
  - use mode stirrer or scattering bump
  - closer node – antinode → **heat transfer** helps!
  - disadvantages
    - high cost
    - need additional shielding



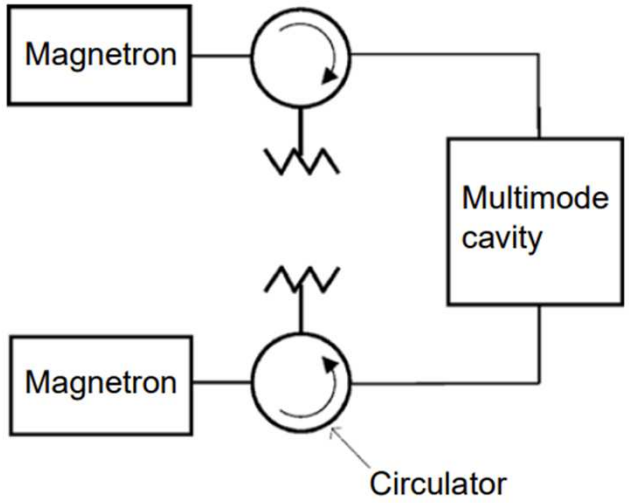
Multi-mode cavities

Heating uniformity

- **Field uniformity** is not the only one.
- example) extremely large load
  - **large** fill factor: large size / high-loss (e.g. foods)
  - close to feed point → hot spot (bad uniformity)

  → use multiple port (problem: coupling between sources)

  → use turntable (problem: circularly symmetrical)



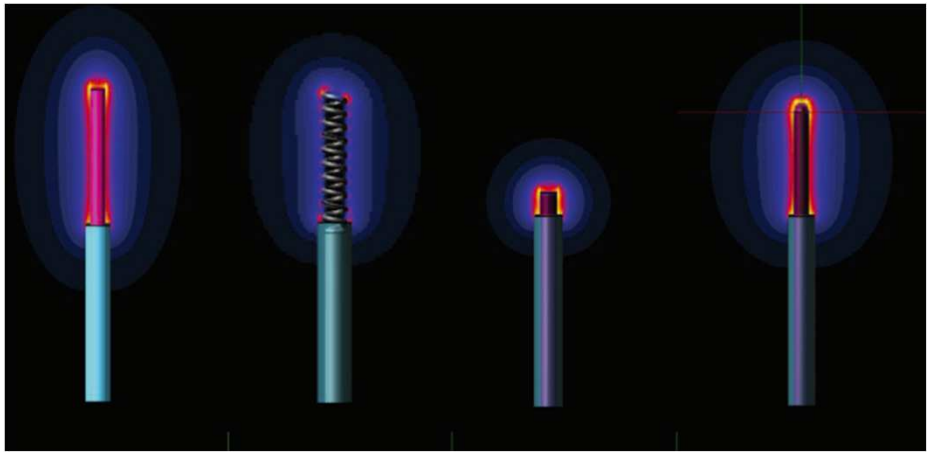
diverting reflected power to dummy load by using circulator for multiple sources

- small penetration depth → stop multi-mode operation (no field beyond the load)

Multi-mode cavities

Heating uniformity

- **Field uniformity** is not the only one.
- geometry of load
  - edge or elongated ends → more enhanced field

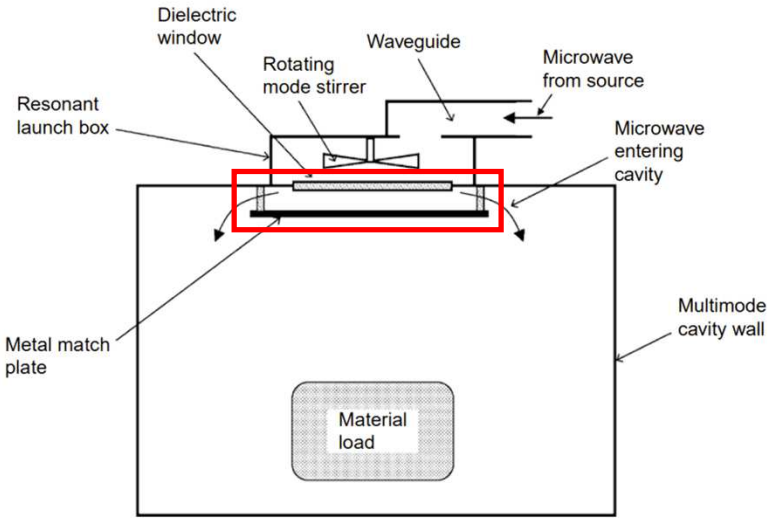


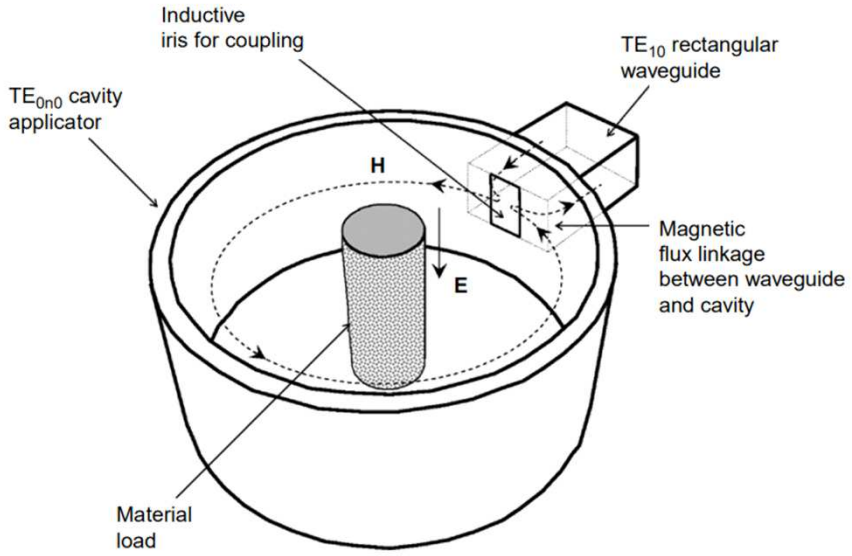
Induced E-field distributions at the lead tips for different tip shapes

Multi-mode cavities

Heating uniformity

- **Field uniformity** is not the only one.
- polarization of modes / coupling
  - coupling method (using iris or loop)에 따른 polarization property 고정
  - solution: use distributed coupling aperture → # of mode ↑, spatial uniformity ↑





SEOULTECH

CEMLAB