CHAPTER 5

Design of Synthetic Microstrip at Higher Order Using Periodic Varactor Loadings

5.1 The Structure of Beam-Steering Micro-Slotline Leaky Wave Antennas

This section presents a periodic, capacitor-loaded micro-slotline leaky wave antenna, as shown in Fig. 5.1, which produces a steerable beam varied by the external loading capacitance (or inductance). Figure 5.1 shows the novel beam-controlled antenna flipped upside down for a clearer view; Metal-Insulator-Metal (MIM) capacitors or varactors are placed across the slotline to control the beam. The microstrip is printed on the opposite side of the slotline and governs the radiation of the EH_1 leaky mode. When no reactive loading is present, the structure is reduced to that of the so-called micro-slotline antenna, of which the dispersion characteristics have been thoroughly examined [57]. Figure 5.2 describes the complex propagation constants ($\gamma=j\beta+\alpha$) of the first higher-order EH_1 mode by the full-wave integral equation method [57], using the following properly chosen material and structural parameters; w = 1 mm, s = 0.4 mm, b = 16 mm, z1 = 3 mm, h = 0.762 mm, H = ∞, and ε_r = 2.55. The beam-controlled leaky-wave antenna will be qualitatively discussed, and then the antenna design concept will be validated by comparing the measured and theoretical results.

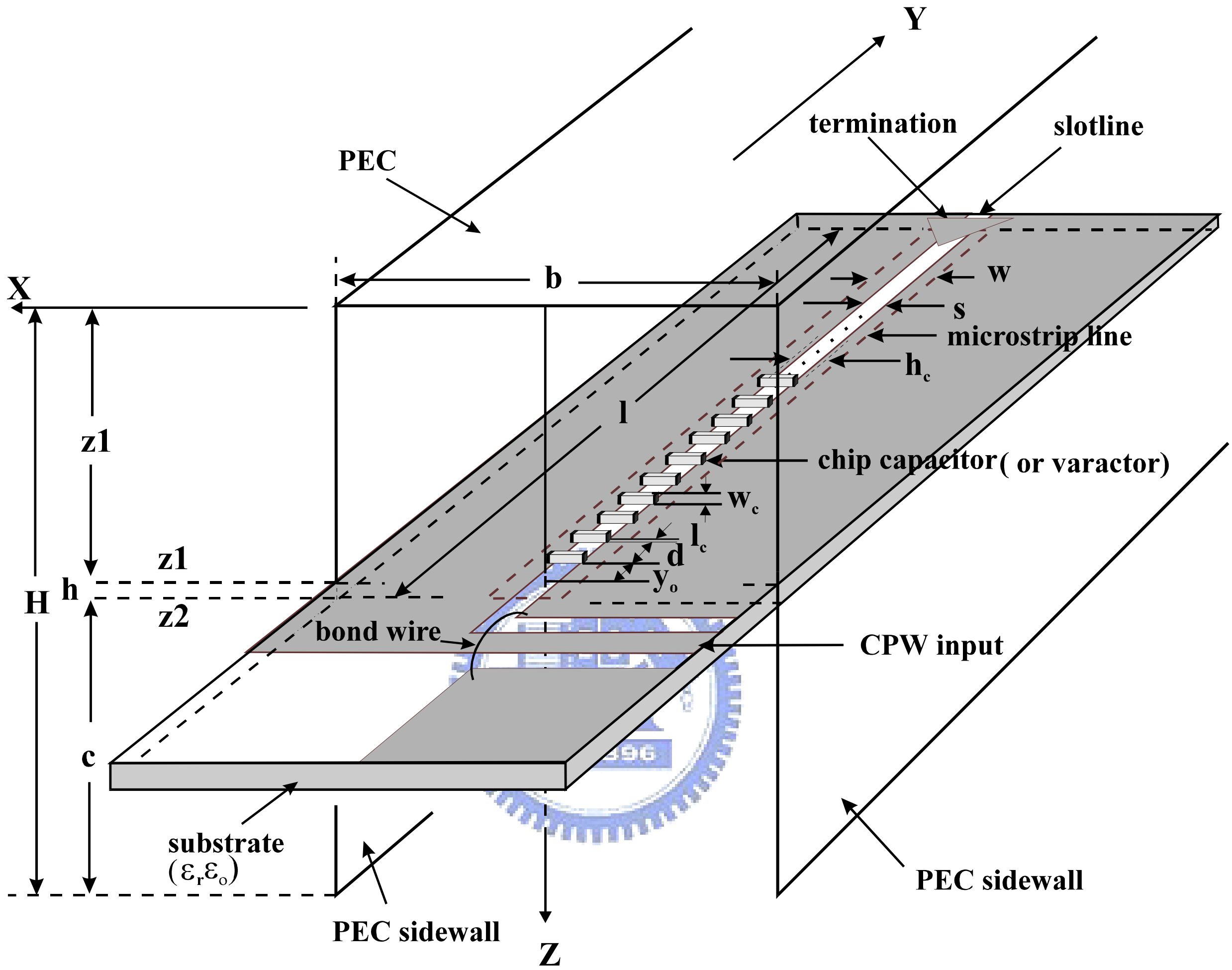


Fig. 5.1. Detailed view of beam steering micro-slotline leaky-wave antenna flipped upside down.

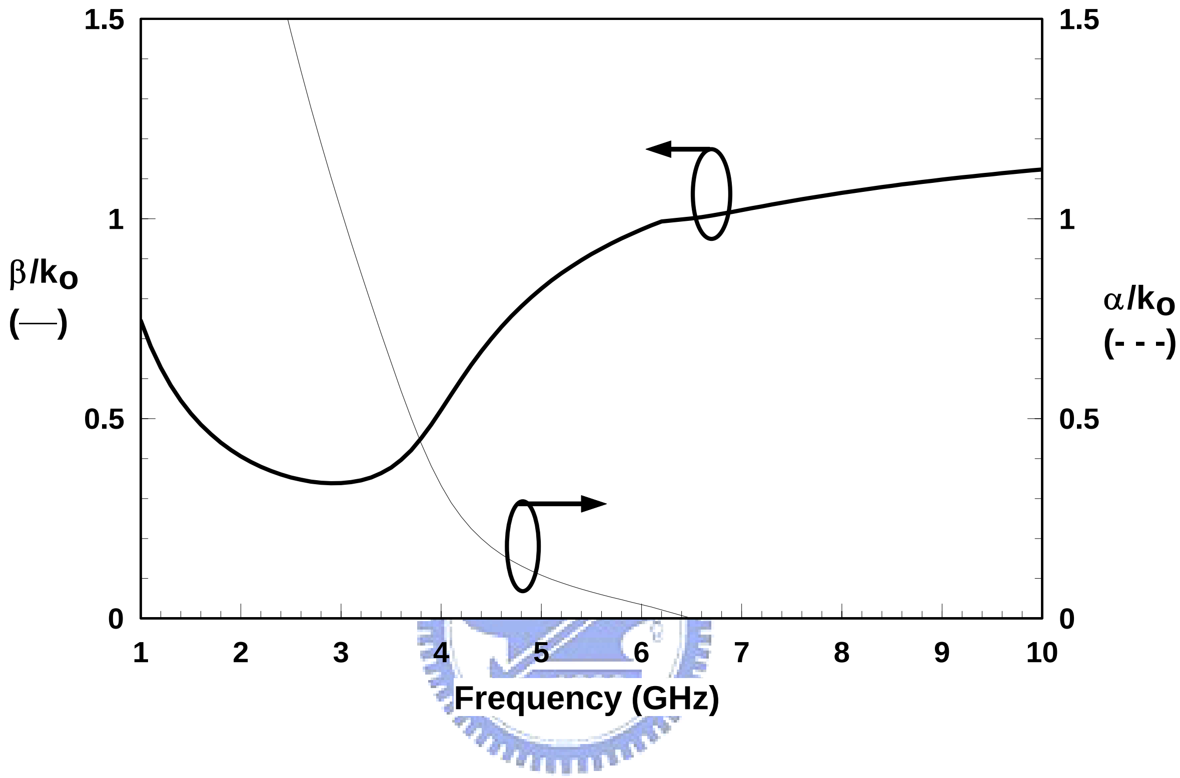


Fig. 5.2. The dispersion characteristic of the first higher order EH_1 mode of uniform, unloaded micro-slotline structure.

W = 1 mm, s = 0.4 mm, b = 16 mm, z1 = 3 mm, h = 0.762 mm, ε_r = 2.55, H = ∞.

—— Normalized phase constant (β / k_o)

----- Normalized attenuation constant (α / k_o).

5.2 Capacitor-Loaded EH_1 Mode and Its Model

According to Fig. 5.1, the input signal propagates along the coplanar waveguide (CPW), and then along the CPW-to-slotline transition, which properly excites the first higher-order EH_1 mode of the micro-slotline [57], [58]. The circuit property of the leaky micro-slotline can be fully modeled by knowing the complex propagation constant and the complex characteristic impedance. The procedure for obtaining the complex characteristic impedance (Z_c) of the leaky line parallels that described by N. K. Das in [59]. Accordingly, the equivalent series radiation resistance (R), series inductance (L), shunt radiation conductance (G) and shunt capacitance (C) per unit length, are related to γ and Z_c of the leaky line by the following expressions.

$$Z_c = \sqrt{(R + j\omega L)/(G + j\omega C)} \tag{5.1}$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta \tag{5.2}$$

The insertion of capacitors (or varactors) at intervals of *d*, much less than the free-space wavelength, essentially changes the guiding characteristics by increasing the shunt capacitance per unit length. Thus, the phase constant (β) increases and the magnitude of Z_c decreases. When β increases, the main beam of the leaky-wave antenna moves toward the horizon (end-fire), at an angle approximated by $\sin^{-1}(\beta/k_o)$, measured from the broadside (z-axis).

A prototype was built using a ROGERS ULTRALAM® ULTRA 2000 substrate with $\varepsilon_r = 2.55$ and thickness h = 0.762 mm. Figure 5.2 shows the structure and material parameters of the leaky-wave antenna, except that the sidewalls' height is H = 28 mm and the antenna length is l = 220 mm. MIM capacitors, made of 20-mil (0.508 mm) ARLON CU-CLAD® 250 substrate ($\varepsilon_r = 2.5$) with a surface area of 1 mm by 1.5 mm, are inserted across the slotline at 2.5 mm intervals. The design includes a total of 79 capacitors.

5.3 Experiments and Theoretical Verification

An experimental beam steering micro-slotline leaky-wave antenna was fabricated and tested following the theoretical analyses and design outline in the preceding section. At first, the operational frequency, f_o, is chosen to be in the leaky region ($f_o < f_{on\text{-}set}$, where $f_{on\text{-}set} = 6.5$ GHz) of the antenna EH_1 mode, as shown in Fig 5.2. The measured input reflection coefficients $|S_{11}|$ are approximately –5.27 dB and –5.81 dB for the unloaded and loaded leaky-wave antenna at $f_o = 4$ GHz, respectively.

Figure 5.3 presents the measured and theoretical radiation H-plane (y-z plane) patterns at 4 GHz, with and without the added capacitors. Theoretical calculations were by the normal full-wave three-dimensional integral equation method [60]. Measurements agree closely with theoretical results. The unloaded tilt angle, θ ($\theta \sim \sin^{-1}\beta/k_o$), is 34° (32.5°) for the measured (simulated) main-beam radiation pattern. As expected, the loaded tilt angle, θ_p ($\theta_p \sim \sin^{-1}\beta_p/k_o$), is 57° (62.5°) for the measured (simulated) main-beam radiation pattern. A beam steering angle of 23° is obtained by merely adding the 0.06527-pF capacitors across the slotline. From the measurements and theoretical results, display multi-beam phenomenon that is obvious for the periodic, capacitor-loaded case.

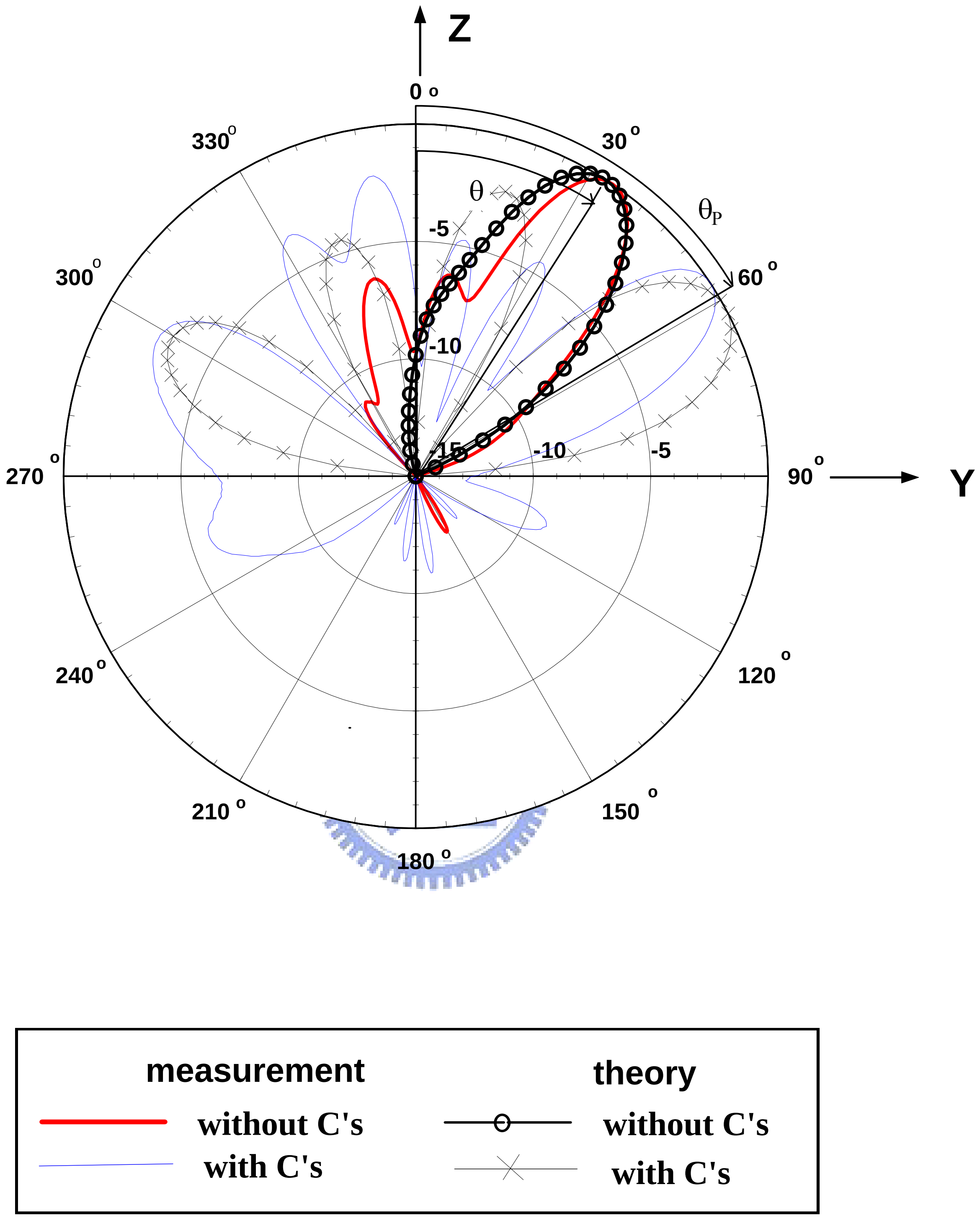


Fig. 5.3. H-plane (Y-Z plane) radiation patterns of the micro-slotline antenna, without and with capacitors, at f_o = 4 GHz.

An electronic beam steering control by varying direct current (D.C.) voltage is established by replacing the 79 MIM capacitors with four varactor diodes (M/A-COM MA46470, constant Gamma = 1.25). The electronic beam-steering micro-slotline leaky-wave antenna structure displays as Fig. 5.4, the structural parameters also list in the legend of Fig. 5.4.

A prototype was built using a Polyflon Co. CuFlon substrate with $\varepsilon_r = 2.1$ and thickness h = 0.762 mm. DC-blocking MIM capacitor, made of 8-mil (0.2032 mm) RT/Duriod 6010 substrate ($\varepsilon_r = 10.2$) with a surface area of 2.19 mm by 2.19 mm, was series connection with varactor diode, which is named DC-blocking varactor, then inserted across the slotline at 20 mm intervals.

Figure 5.5 shows the measured scattering parameter S_{11} and input impedance Z_{11} versus frequency response for the electronic beam-steering antenna at different reverse bias cases (V_r = 1, 3, and 5-Volts). From the result of Fig. 5.5(a), displays a good input matching, the magnitude of input reflection coefficient $|S_{11}|$ smaller than –10 dB in the 3.0 - 3.6 GHz band for the three cases. From the results of Fig. 5.5(b) - (c), demonstrate the resonant frequency f_{res} that simultaneously satisfies the conditions of the phase of S_{11}, Ang(S_{11}), equal zero, the real part of Z_{11}, Re(Z_{11}), attain maximum, and the imaginary part of Z_{11}, Im(Z_{11}), equal zero, toward the lower frequency for the smaller reverse bias case, the resonant frequency is about 3.1, 3.23, and 3.315 GHz, and the maximum of

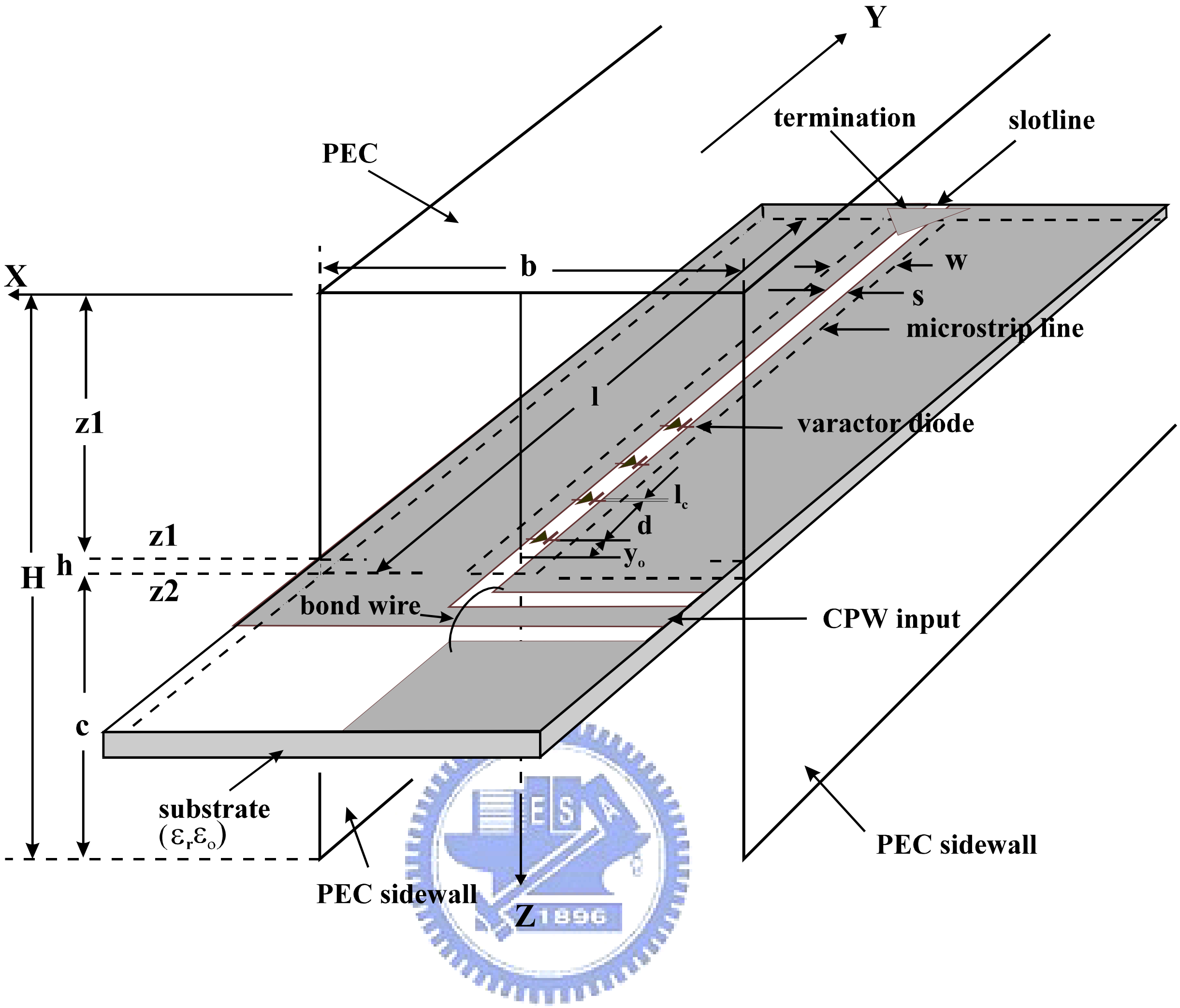
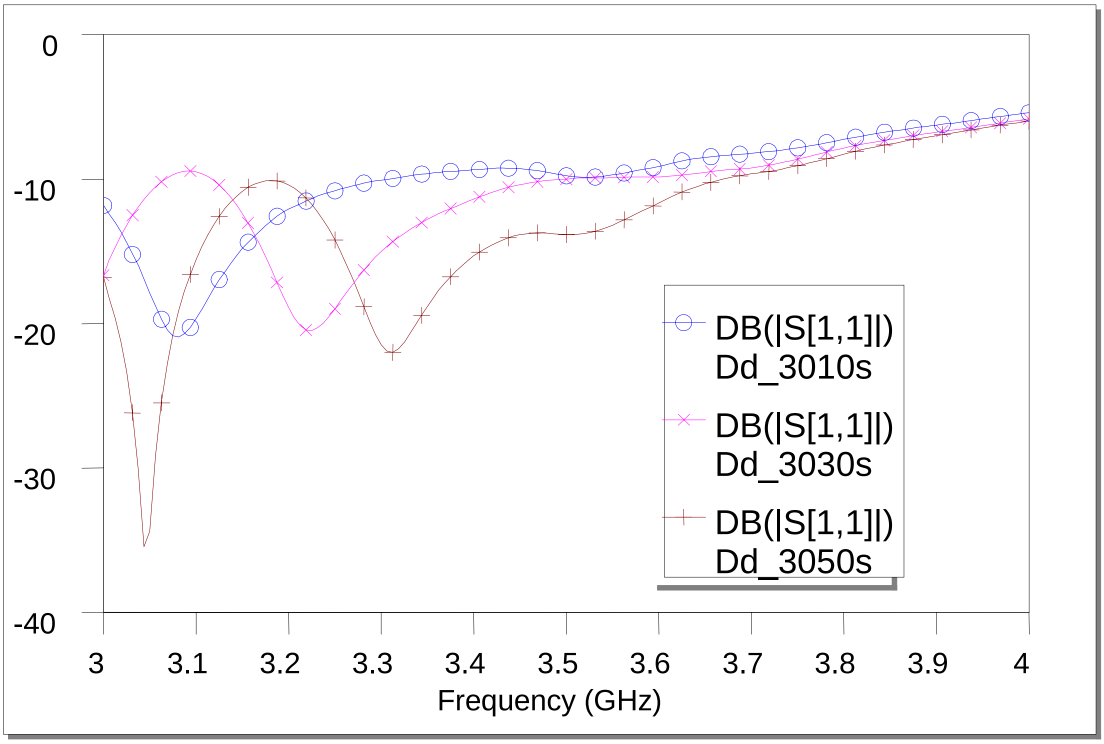
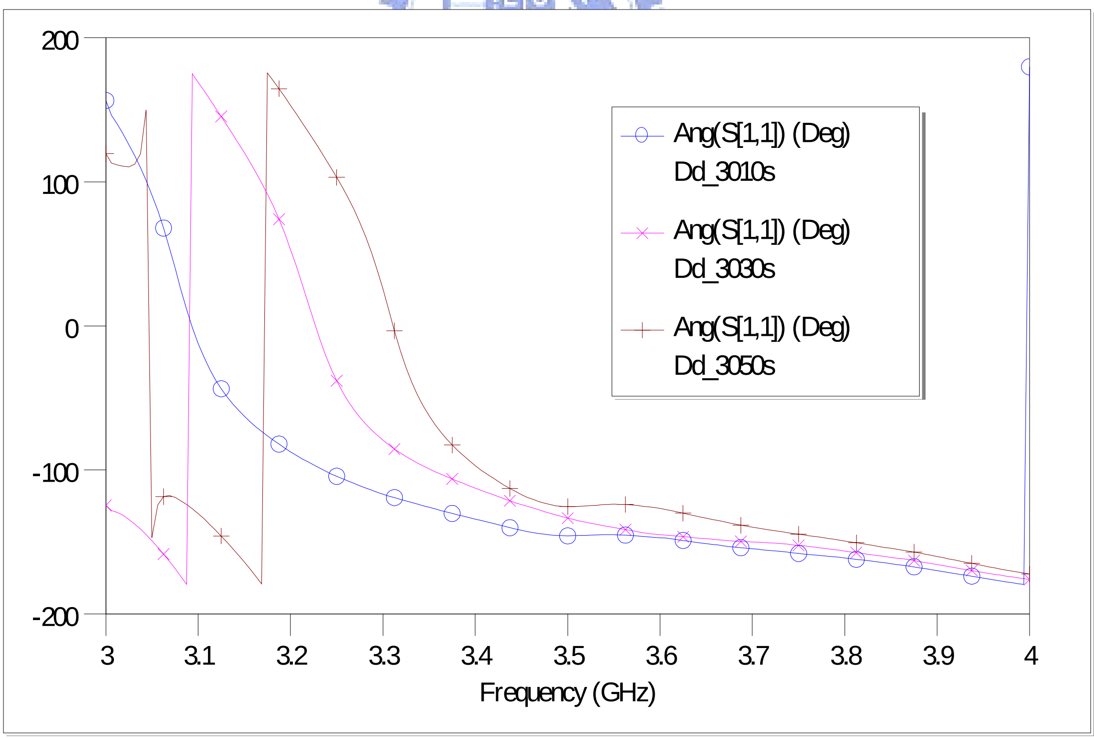


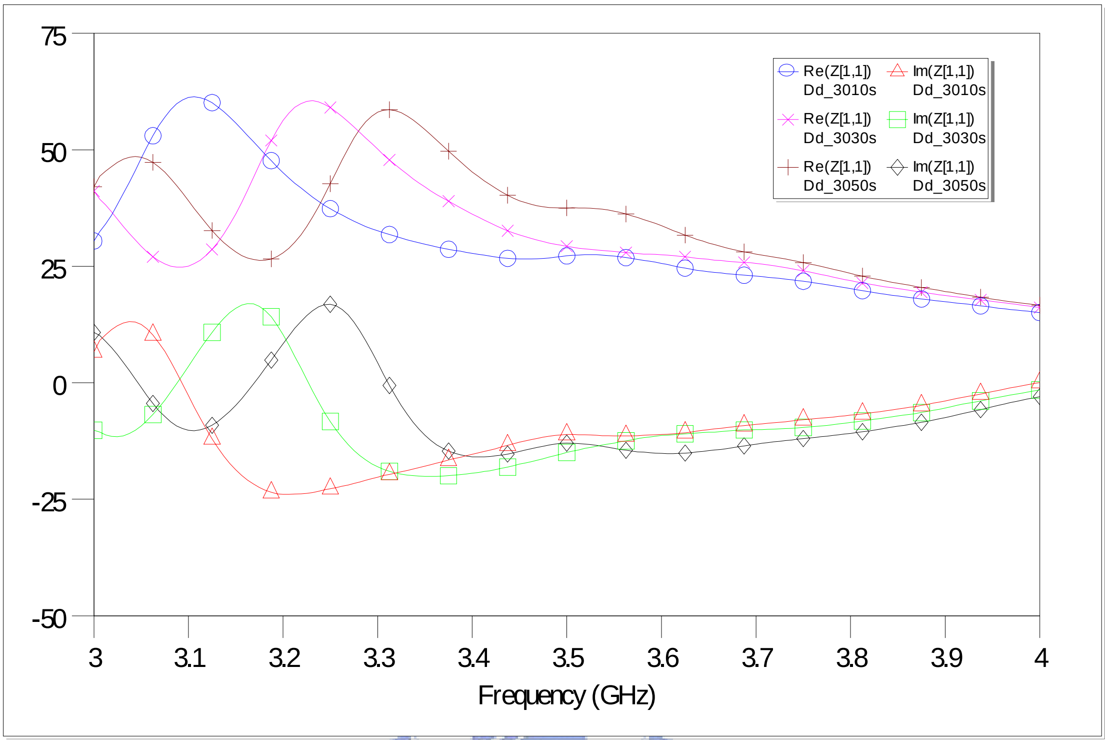
Fig. 5.4. The electronic beam steering leaky-wave antenna construction: the micro-slotline leaky-wave antenna with parallel varactors and the uniplanar feed viewed upwardly from physical original structure. The reverse bias and DC-blocking capacitors doesn’t display in Fig. 5.4. The structure parameters are w = 1 mm, s = 0.4 mm, b = 16 mm, z1 = 3 mm, H = 28 mm, h = 0.762 mm, ε_r = 2.1, y_o = 3.5 mm, l_c = 1 mm, d = 20 mm.



(a) The magnitude of S_{11} Scattering Parameter



(b) The phase of S_{11} Scattering Parameter



(c) The input impedance

Fig. 5.5. The measured result**:** (a) magnitude of S_{11}, (b) phase of S_{11}, and (c)-input impedance of the electronic beam steering leaky-wave antenna as Fig 5.4. (Dd_3010s, Dd_3030s and Dd_3050s represent reverse bias V_r = 1-Volt, 3-Volts, and 5-Volts applying to the DC-blocking varactors cases, respectively.

$Re(Z_{11})$ is about 62, 59, and 57.5 Ω at f_{res}, for the V_r = 1, 3, and 5-Volts, respectively.

Figure 5.6 presents the measured angle of the main beam, against the reverse D.C. bias. The results also shows the main beam of the electronic beam-steering antenna toward the horizon (end-fire) direction for the smaller reverse bias case that is larger loading capacitance, the angle of main beam θ_p is 35.2°, 29.9°, and 21.6° for the V_r = 1, 3, and 5-Volts, respectively. An electronic beam steering angle of 13.5° is obtained by merely adding four DC-blocking varactors, across the slotline for the V_r = 1 - 5 Volts.

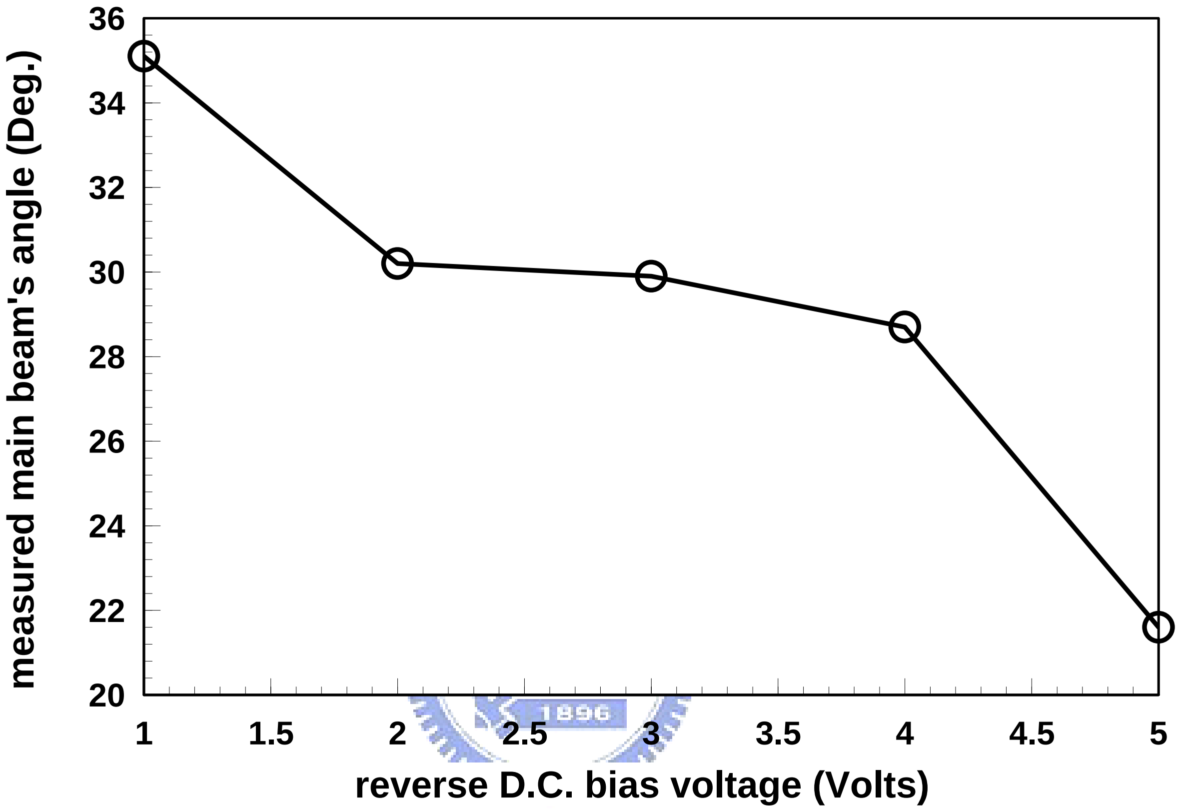


Fig. 5.6. The measured main beam’s angle against reverse D.C. bias voltage of the electronic beam steering micro-slotline leaky wave antenna, at f_o = 3 GHz.