FACULTY OF
ELECTRONICS, TELECOMMUNICATIONS, AND INFORMATION TECHNOLOGY
Department of Telecommunications and Information Technology
Laboratory of Antennas and Propagation

Prof. dr. ing. Ion BOGDAN

PATCH ANTENNA DESIGN

IAȘI, 2017

The information included in this presentation and the associated software programs are selected from

R.A. Sainati – *CAD of Microstrip Antennas for Wireless Applications*, Artech House, 1996

Basic Structure

Figure no. 1 illustrates the basic microstrip structure. It consists in a rectangular dielectric substrate with relative electric permittivity ε_r and loss tangent $\tan\delta$, whose lower surface is covered by a conducting stratum. The conducting stratum is applied by using an electrochemical deposition process or by using special adhesives. Initially, the upper surface is also covered by a conducting stratum, but this one is partially eliminated by corrosion, except for a rectilinear region of width *w*. The thickness *t* of the conducting stratum varies between 0.0007 inches (0.00178 cm) and 0.0014 inches (0.00356 cm), while the dielectric height *h* varies between 0.002 inches (0.05 cm) and 0.25 inches (0.635 cm).

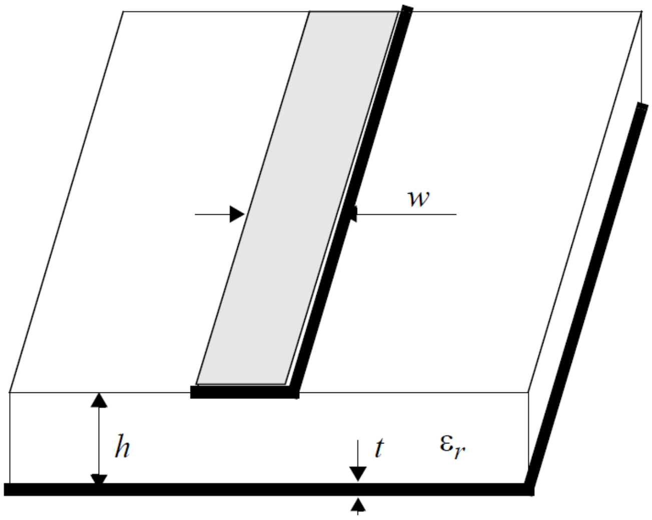

Figure no. 1 – *Microstrip basic structure*

The two conducting surfaces and the dielectric between them constitute a guided medium of electromagnetic wave propagation. In order to allow the propagation of the fundamental transversal mode (TEM) only, the height *h* of the dielectric is chosen as a small percent (about 2%) of the wavelength. If the width of the upper conducting band is constant and the length of the structure is infinite, then there is no electromagnetic radiation outside the structure. Radiation appears only in regions where the width of the conducting band suffers fast variations. *Microstrip antennas are conducting areas on the upper surface of the basic structure from figure no. 1 with large variations of the dimension transversal to the wave propagation inside the supporting dielectric.*

Figure no. 2 illustrates the structure of a rectangular patch antenna. The conducting band operates as a feeding microstrip line for the rectangular patch antenna. Radiation appears at the joint edge between the microstrip line and the rectangular patch, as well as at the opposite edge of the patch. Rigorously, there is radiation along the other edges, too, but it is negligible small.

Advantages of microstrip antennas:

- they have extremely small dimensions, allowing for their incorporation into an equipment case;
- for a flexible dielectric substrate the could occupy an arbitrary shaped space inside an equipment case or they could even constitute the equipment cover walls;
- they have a small weight;
- production cost is low as it is not necessary to process large metallic blocks.

- fabrication process assures very small variations of individual antenna parameters because the photolithographic corrosion is a tight controlled process and the antennas' dimensions result with extremely great accuracy;
- antenna and its feeding line fabrication process could be integrated with the one of the associated electronic equipment (receiver or transmitter) because they are based on the same physical and chemical phases: metallic deposition and corrosion, diffusion, etc. Moreover, the antenna and its feeding line could be realized on the same silicon substrate as the RF part of the electronic circuit (monolithic antennas).

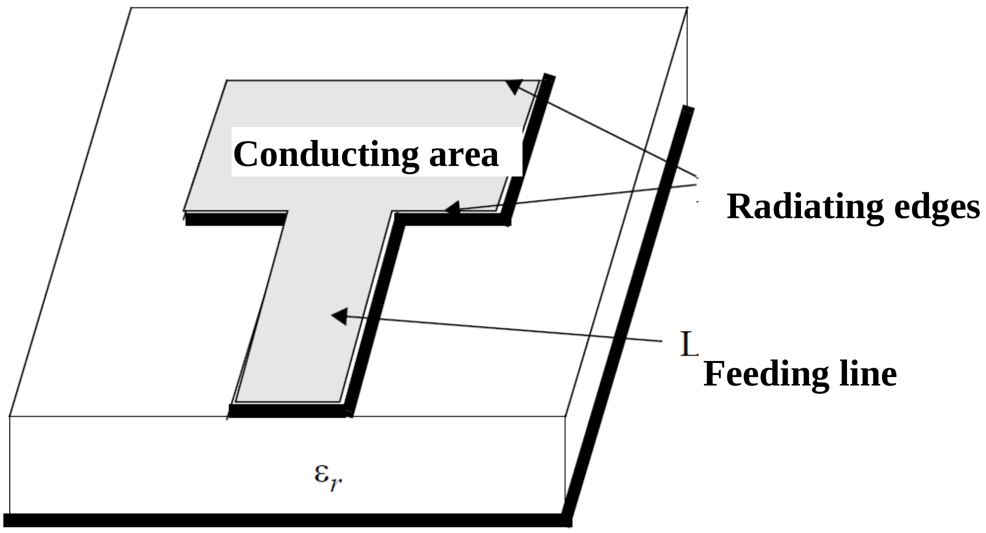

Figure no. 2 – *Radiative microstrip structure (patch antenna)*

There are some *disadvantages*, too:

- frequency bandwidth is very small. Usually, the Q factor is between 50 and 75 and, for a maximum allowed standing wave ratio of 2:1, the corresponding frequency bandwidth is only 1 – 5 % from the radiated wave frequency;
- the side lobes' level of the radiation pattern of the arrays of microstrip antennas is difficult to control due to the above mentioned small frequency bandwidth; moreover the array radiation pattern could be significantly influenced by the presence of numerous feeding lines for individual antennas;
- feeding line is usually made as a microstrip line, which presents big losses and so, microstrip antenna as a whole has small radiation efficiency.

Application domains

Microstrip antennas are used in applications where small dimension, small weight, and, possible, flexible shape are of main importance. Some of the usual domains are the following:

- telemetry and communications with flying objects (airplanes, satellites, rockets);
- airplane altimeters;
- radio communications and navigation;
- aerial topography;
- naval communications;
- automatic guiding of intelligent weapons;
- positioning systems (GPS, Galileo).

Patch Antenna Modeling

Although the structure of the patch antenna is quite simple its modeling is complex task due to presence of the dielectric substrate and the conducting stratum on the surface opposite to the antenna. There are simple models for some very simple structures of antennas that offer some qualitative information about the antenna and there are some other complex models that allow for precise design of more complex structures as microstrip antennas. The latter models use integral and differential equations quite difficult to solve and thus difficult to use and this is why the simpler models continue to be used extensively.

Microstrip Transmission Line

One of the most used models for the patch antenna is the one based on its equivalence with a microstrip transmission line whose basic structure is presented in figure no. 1. A cross section of this structure is presented in figure no. 3. There is illustrate in the figure the shape of the field lines corresponding to the transversal electromagnetic mode, the only mode allowed to propagate through the structure for appropriate chosen dimensions. Notice that most of the electric field lines are completely inside the dielectric, but the ones that start on the lateral and on the upper surface of the conductive band have part of the line outside the dielectric. Most part of any magnetic field line is outside the dielectric.

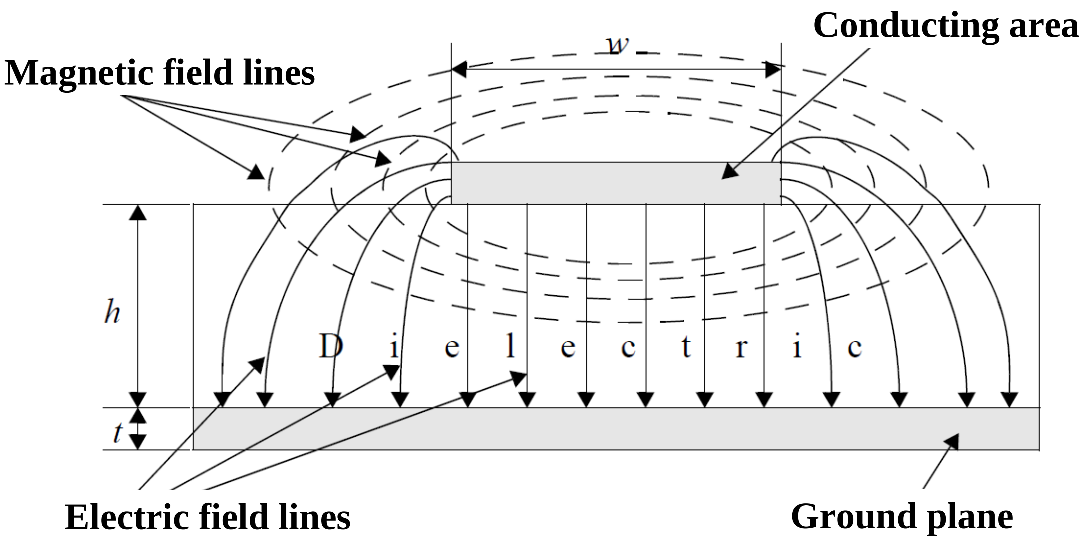

Figure no. 3 – *Patch antenna cross section*

This extension of the field lines in the medium surrounding the dielectric has significant effects. Thus:

- the electromagnetic field propagating through the structure is not purely transversal, but it has a longitudinal component. This component could be neglected for a rough modeling of the transmission line operation, but it has to be taken into consideration when accurate modeling is needed;
- the equivalent permittivity of the structure differs slightly from the one of the dielectric. The difference depends on the fraction of the lines length that is outside the dielectric and is function of microstrip line width *w*, the height h of the dielectric, and the permittivity ε of the dielectric.
- the parameters of the microstrip line vary with frequency (phenomenon denoted as *dispersion*). This is due to the fact that the shape of field lines depends on the ratio of the physical dimensions to the field wavelength and the latter one varies with

frequency. As a result the fraction of the field lines that is outside the dielectric varies with frequency and the microstrip line equivalent permittivity varies accordingly. The dispersion is negligible small for frequency below 8 GHz and for small values of the dielectric height h.

The theoretical and experimental studies conducted on microstrip lines aimed at establishing formulas for its relative electric permittivity ε_{re} and its characteristic impedance Z_0. With acceptable accuracy we have:

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} F\left(\frac{w}{h}\right) - C \tag{1}$$

$$Z_0 = \frac{\eta_0}{2\pi\sqrt{\varepsilon_{re}}} \ln\left(\frac{8h}{w_e} + \frac{w_e}{4h}\right), \qquad \text{for } \frac{w}{h} \le 1 \tag{2}$$

$$Z_0 = \frac{\eta_0/\sqrt{\varepsilon_r}}{\frac{w_e}{h}+1.393+0.667\ln\left(\frac{w_e}{h}+1.444\right)}, \quad \text{for } \frac{w}{h} > 1 \tag{3}$$

where:

$$F\left(\frac{w}{h}\right) = \frac{1}{\sqrt{1+\frac{12h}{w}}} + \frac{\left(1-\frac{w}{h}\right)^2}{25}, \qquad \text{for } \frac{w}{h} \le 1 \tag{4}$$

$$F\left(\frac{w}{h}\right) = \frac{1}{\sqrt{1+\frac{12h}{w}}}, \qquad \text{for } \frac{w}{h} > 1 \tag{5}$$

$$C = \frac{\varepsilon_r-1}{4.6} \frac{t/h}{\sqrt{w/h}} \tag{6}$$

$$\frac{w_e}{h} = \frac{w}{h} + \frac{1.25}{\pi}\frac{t}{h}\left(1 + \ln\frac{4\pi w}{t}\right), \quad \text{for } \frac{w}{h} \le \frac{1}{2\pi} \tag{7}$$

$$\frac{w_e}{h} = \frac{w}{h} + \frac{1.25}{\pi}\frac{t}{h}\left(1 + \ln\frac{2h}{t}\right), \quad \text{for } \frac{w}{h} > \frac{1}{2\pi} \tag{8}$$

$\eta_0 = 120\pi \approx 377$ ohms is the free space characteristic impedance.

If we admit that the relative permeability $\mu_r = 1$, then the delay introduced by a microstrip line of length *l* is:

$$kl = \frac{2\pi}{\lambda} l = \frac{2\pi}{\lambda_0} l\sqrt{\varepsilon_{re}} \tag{9}$$

where λ_0 is the free space field wavelength and $\lambda_0/\sqrt{\varepsilon_{re}}$ is the wavelength of the field propagating through the microstrip line.

For frequencies above 8 GHz the phenomenon of dispersion should be taken into account, this meaning that the equivalent electrical permittivity varies with frequency and, as a result, the microstrip line characteristic impedance and the field wavelength through the microstrip line change accordingly.

The electromagnetic field propagating through the microstrip line suffers an attenuation of its modulus due to losses in the conducting band and in the ground plane as well as in the dielectric. This attenuation in dB/meter could be computed by means of the following approximate formulas:

$$\alpha_c = 1.38A\frac{R_S}{hZ_0}\frac{(32-w_e/h)^2}{(32+w_e/h)^2}, \qquad \text{for } \frac{w}{h} \le 1 \tag{10}$$

$$\alpha_c = 6.1\cdot 10^{-5} A\frac{R_S Z_0 \varepsilon_{re}}{h}\left(\frac{w_e}{h} + \frac{0.667 w_e/h}{1.444+w_e/h}\right), \quad \text{for } \frac{w}{h} > 1 \tag{11}$$

$$\alpha_d = 27.3 \frac{\varepsilon_r}{\varepsilon_r - 1} \frac{\varepsilon_{re} - 1}{\sqrt{\varepsilon_{re}}} \frac{\tan\delta}{\lambda_0} \tag{12}$$

where

$$A = 1 + \frac{h}{w_e}\left(1 + \frac{1.25}{\pi} \ln \frac{2\pi w}{t}\right), \qquad \text{for } \frac{w}{h} \leq \frac{1}{2\pi} \tag{13}$$

$$A = 1 + \frac{h}{w_e}\left(1 + \frac{1.25}{\pi} \ln \frac{2h}{t}\right), \qquad \text{for } \frac{w}{h} > \frac{1}{2\pi} \tag{14}$$

$$R_S = \sqrt{\pi f \mu_0 / \sigma} \tag{15}$$

where σ is the conductivity in Siemens/meter of the material for the ground plane and the upper strip band and $\mu_0 = 4\pi 10^{-7}$ Amperes/meter is the free space magnetic permeability.

Total attenuation is $\alpha = \alpha_c + \alpha_d$.

Therefore, after propagating along a microstrip line of length l, an input electromagnetic wave of amplitude V_0 suffers an attenuation $e^{-\alpha l}$ and a phase delay of $e^{-j\beta l}$, that is:

$$V(l) = V_0 e^{-\alpha l} e^{-j\beta l} = V_0 e^{-kl} \tag{16}$$

The characteristic impedance Z_0 and the propagation constant $k = \alpha + j\beta$ completely describe a microstrip transmission line.

As previously mentioned the above results are true when only the transversal electromagnetic wave propagates through the microstrip structure. Rigorously, the structure allows for propagating other modes, too (especially the transversal magnetic mode TM_0) that constitute the so denoted *surface wave*. So parasitic radiation appears and also coupling phenomena among different microstrip lines realized on the same dielectric. In order to keep these undesired effects the height of the dielectric should fulfill the following requirement:

$$h \leq \frac{c}{4f\sqrt{\varepsilon_r - 1}} \tag{17}$$

where c is the free space light velocity.

A resonant mode could appear along the width of the microstrip line with frequency:

$$f_c = \frac{c}{\sqrt{\varepsilon_r}(2w + 0.8h)} \tag{18}$$

yielding a voltage with maximum values at microstrip line lateral edges a null value in the middle plane. This mode determines quite big values for the loss in the useful transversal electromagnetic mode and, therefore, the microstrip line width should be carefully chosen such that the frequency given by formula (18) be much greater than the maximum operating frequency.

Discontinuities

Any change in a microstrip line width or in its direction, as well as junction of two or more line segments represent discontinuities. They modify electrical properties of the microstrip line and efforts were made to model these changes, usually represented by means of equivalent electrical circuits. The resistors in these circuits models the supplementary losses introduced by a discontinuity and the useful effect of radiation outside the structure, the capacitors model the accumulation of electrical charges along the edges of the discontinuity that cut electric filed lines, while the inductors model the effect of cutting magnetic field lines. The parameters of a model are computed as related to reference plane.

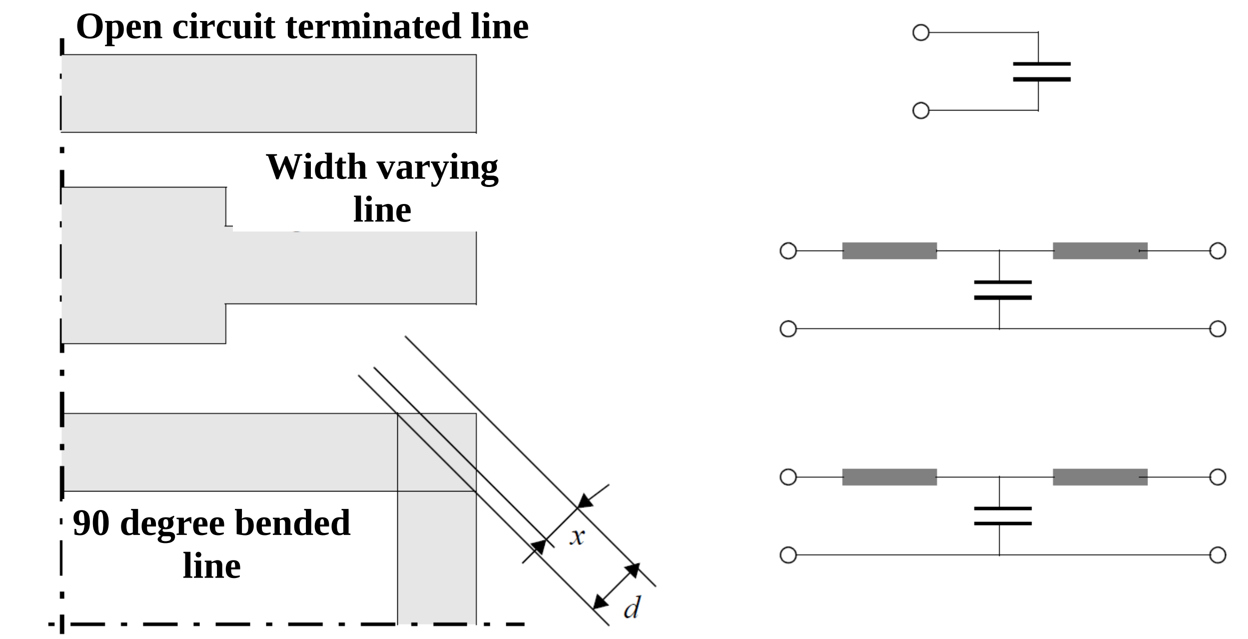

Figure no. 4 – *Equivalent circuits for usual discontinuities*

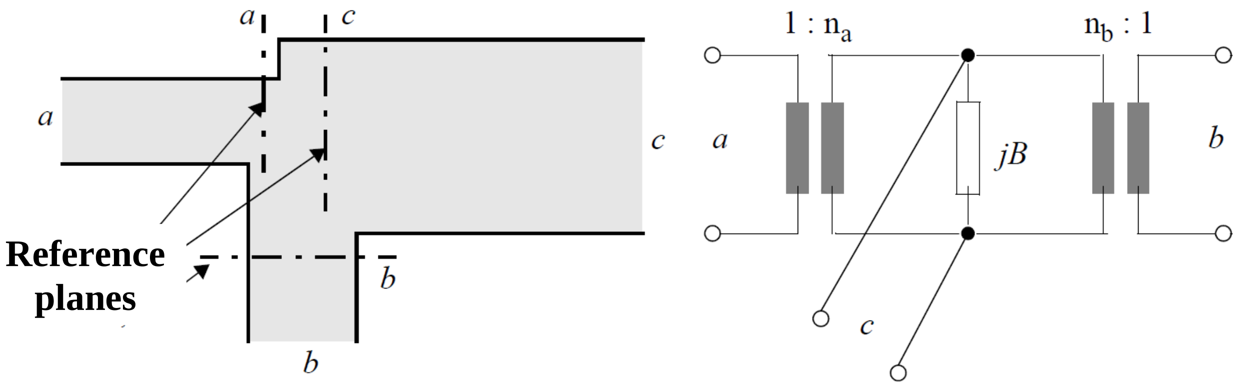

Figure no 5 – *Equivalent circuit for T junction*

Figures no. 4 and no. 5 present some typical discontinuities and their associated models. The recommended tap at direction change in a right angle is intended for decreasing the big value of inductance that is induced by the direction change. The tap length x is computed with the following formula:

$$x = \left(0.52 + 0.65e^{-1.35w/h}\right)d \tag{19}$$

Transmission Line based Model for Patch Antenna

The basic structure of a patch antenna fed by means of microstrip transmission line is presented in figure no. 6. The antenna is a rectangle with length *L* and width *W*. The feeding transmission line width is denoted as *w*. The dimension change in width at junction between line and antenna is a discontinuity that allows for electromagnetic field radiation through the antenna edge not blocked by the transmission line. Also, the open end termination of antenna at the end opposite to the transmission line junction is a radiative edge of the antenna. There is a parasitic radiation long the other two edges of the antenna, but it is negligible small.

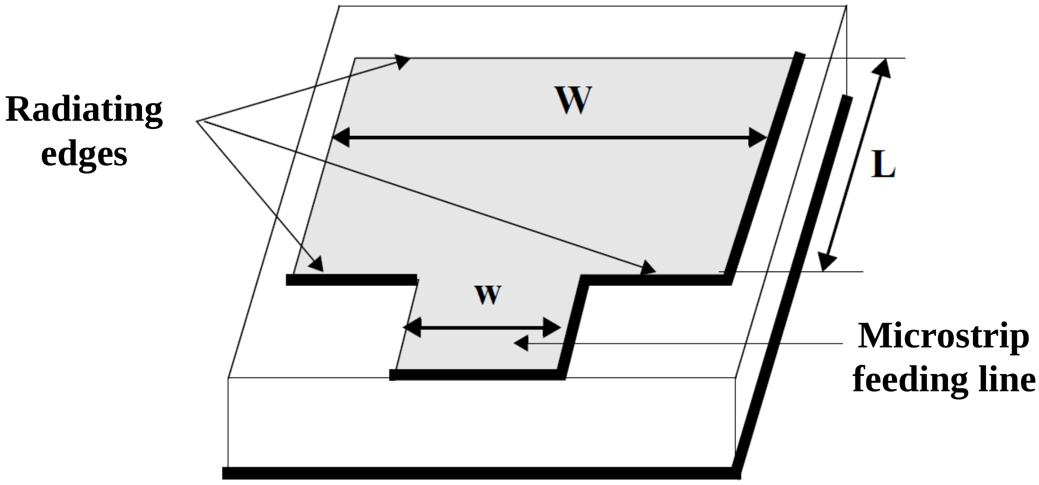

Figure no. 6 – *Microstrip line fed patch antenna*

Regarding the patch antenna as a microstrip transmission line we could build its equivalent circuit model containing elements modeling the physical phenomena associated to the field propagation along the antenna from the junction with the feeding line to the open end termination at the opposite edge (figure no. 7):

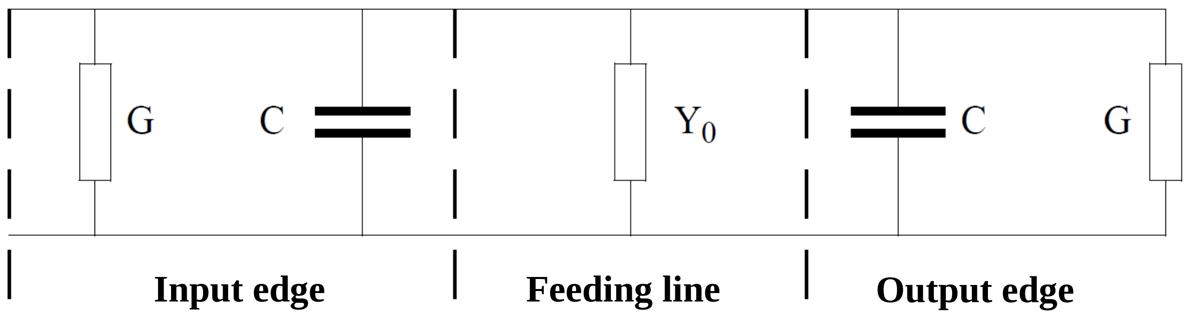

Figure no. 7 – *Equivalent circuit for rectangular patch antenna*

- an input conductance G and capacitance C that model the radiation of the antenna edge connected to the transmission line;
- an output conductance G and capacitance C that model the radiation of the antenna opposite edge;
- the admittance Y_0 of the space between the two edges which is the characteristic admittance of a microstrip line of width W.

Neglecting the attenuation introduced by propagation between the two edges, the antenna input admittance is:

$$Y_{in} = G + jB + Y_0 \frac{G + jB + jY_0 \tan(\beta L)}{Y_0 + j(G + jB)\tan(\beta L)} \tag{20}$$

with $B \triangleq \omega C$.

For an antenna with $L = \lambda/2$ (which is the usual case), admitting that matching conditions are fulfilled at both radiating edges, the last term in the above relation has the imaginary part equal in value with the one at the input edge, but with opposite sign. As a consequence, for this particular case:

$$Y_{in} = 2G \tag{21}$$

The frequency at which the required matching condition is fulfilled is the usual working frequency of the patch antenna.

The purely resistive input impedance at the resonant frequency is physically explained by accumulation of equal amount of electrical charges with opposite sign on the two radiation edges of the antenna.

Evaluation of Model Parameters

Physical parameters of the patch antenna are computed by using relations 1 – 15. Its width *W* is chosen based on the space antenna should occupy inside the equipment case and in accordance with the requirement (18). Its length *L* is determined from the resonance condition at the working frequency:

$$L = \frac{\lambda}{2} = \frac{\lambda_0/\sqrt{\varepsilon_r}}{2} = \frac{\lambda_0}{2\sqrt{\varepsilon_r}} \qquad (22)$$

where λ_0 is the free space wavelength of the radiated field, while λ is the wavelength of the same radiated field in a dielectric with the relative permittivity ε_r.

The capacitance *C* is computed based on the edge effect, that is the length of the extended region outside the one of length *L* occupied by the antenna. If:

$$0.01 \le W/h \le 100 \qquad (23)$$

and $\varepsilon_r \le 128$, then the length of this extended region is:

$$\Delta l = \frac{\eta_1 \eta_3 \eta_4}{\eta_5} h \qquad (24)$$

where:

$$\eta_1 = 0.434907 \frac{\varepsilon_{re}^{0.81} + 0.26(W/h)^{0.8544} + 0.236}{\varepsilon_{re}^{0.81} - 0.189(W/h)^{0.8544} + 0.87} \qquad (25)$$

$$\eta_2 = 1 + \frac{(W/h)^{0.371}}{0.358\varepsilon_r + 1} \qquad (26)$$

$$\eta_3 = 1 + \frac{0.5274 \operatorname{atan}\left[0.084 (W/h)^{1.9413/\eta_2}\right]}{\varepsilon_{re}^{0.9236}} \qquad (27)$$

$$\eta_4 = 1 + 0.5274\left[6 - 5e^{0.036(1-\varepsilon_r)}\right] \operatorname{atan}\left[0.067 (W/h)^{1.456/\eta_2}\right] \qquad (28)$$

$$\eta_5 = 1 - 0.218 e^{-7.5(W/h)} \qquad (29)$$

Because the length Δl of the extended region is extremely small, it could be regarded as an open ended small length transmission line and modeled by a capacitance:

$$C = \frac{\tan(\beta \Delta l)}{\omega Z_0} \qquad (30)$$

where $\omega = 2\pi f$ and $Z_0 = 1/Y_0$.

In order to evaluate the value of the conductance *G* it is necessary to estimate the total radiated power of the patch antenna, because it models the losses in the antenna and the main loss is the one due to radiation of the electromagnetic wave.

For small values of the dielectric height *h* the surface wave effect is negligible small and the radiation of the transversal electromagnetic mode by the two radiant edges of the antenna could be viewed as the radiation of two slot antennas of length *W* and width *h* (figure no. 8) fed by the uniform distributed field created in the antenna dielectric. Each of the slots radiates an electromagnetic field given by the following formulas:

$$E_\theta = V_0 \frac{\sin[(k_0 h/2)\cos\phi]}{(k_0 h/2)\cos\phi} \qquad (31)$$

in the *xOy* plane (containing the antenna length L), and:

$$E_{\phi} = V_0 \frac{\sin[(k_0 W/2)\cos\theta]}{(k_0 W/2)\cos\theta} \tag{32}$$

in the *xOz* plane (containing the antenna width *W*).

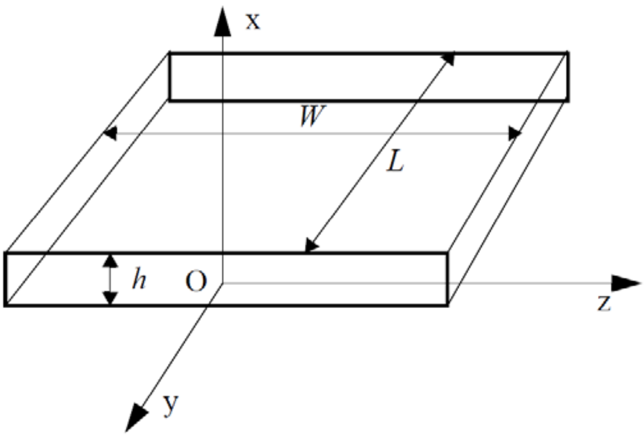

Figure no. 8 – *Cartesian coordinate system used for patch antenna analysis*

$V_0 = hE_0$ is the voltage between the antenna and the ground plane, while E_0 is the electrical field in the antenna dielectric.

Because h is extremely small, $\phi \approx \pi/2$ and $E_{\theta} \approx V_0$ in the *xOy* plane.

Based on the above expressions of the radiated field, we could compute the power density of the radiated field and the total radiated power. Then, we could compute the equivalent conductance *G* of a slot radiating an electromagnetic power equal to the patch antenna total radiated power when the same voltage V_0 between its edges. After some tedious mathematical manipulations we obtain:

$$G = \frac{1}{\pi^2 \eta_0}\left\{\left[w_r \operatorname{Si}(w_r) + \frac{\sin w_r}{w_r} + \cos w_r - 2\right]\left(1 - \frac{s^2}{24}\right) + \frac{s^2}{12}\left(\frac{1}{3} + \frac{\cos w_r}{w_r^2} - \frac{\sin w_r}{w_r^3}\right)\right\} \tag{33}$$

where $w_r \triangleq k_0 W$, $s \triangleq k_0 \Delta l$, and $\operatorname{Si}(w_r) \triangleq \int_{w_r}^{\infty} \frac{\sin x}{x} dx$.

The patch antenna model we discussed earlier approximates quite well its actual operation. But, besides losses induced by the surface wave that we neglected, there is another phenomenon that was not taken into consideration: the *external coupling* between the two radiating slots that is due to the fact that each slot is in the close neighborhood of the other and, thus, radiation process of a slot is influenced by the radiated field of the other slot. The external coupling is modeled by two current sources controlled by a complex admittance $Y_m = G_m + jB_m$, whose parameters are computed by means of complex formulas that include Bessel functions.

Figure no. 9 presents the advanced model of patch antenna that includes the external coupling effects.

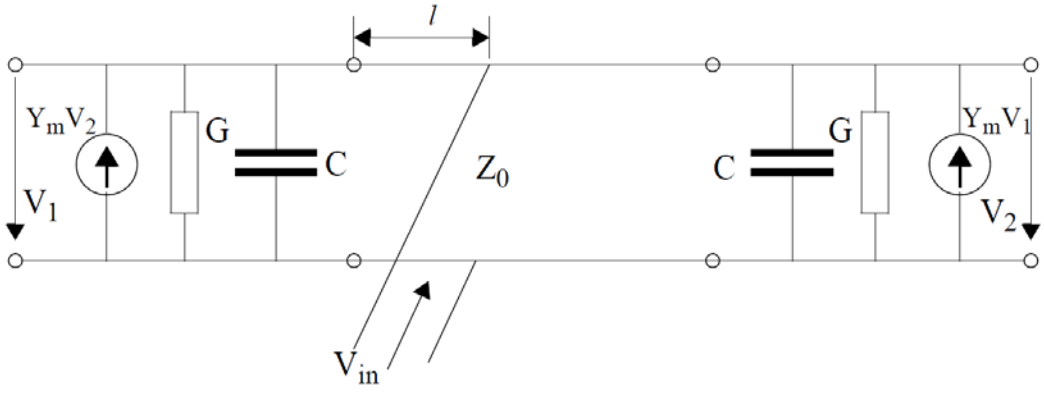

Figure no. 9 – *Advanced circuit model for rectangular patch antenna*

Matching Techniques

Usually, the impedance of the patch antenna in the input plane is about 100 – 300 ohms. On the other hand, standard feeding transmission lines have characteristic impedances of 50 ohms. So, a matching technique should be used at the junction between the feeding line and the patch antenna that allows for a maximum efficiency of the power transfer.

A frequently used matching technique consists in connecting the feeding line to the patch antenna in an inner point, instead of the input edge. This technique takes advantage of the fact that the patch antenna impedance decreases continuously from a maximum value in the plane of the input edge to 0 in the middle plane and increases again to the same maximum value in the plane of the output edge. This is the consequence of the standing wave regime that appears in the dielectric after the total reflection of the field at the open end termination. For $L = \lambda/2$ the standing wave has a maximum at the input edge, decreases monotonically to 0 in the middle plane and increases monotonically the same maximum value at the output edge. The voltage and the impedance between an antenna point and the ground plane vary accordingly. So, we could always find an inner point where the antenna impedance is 50 ohms.

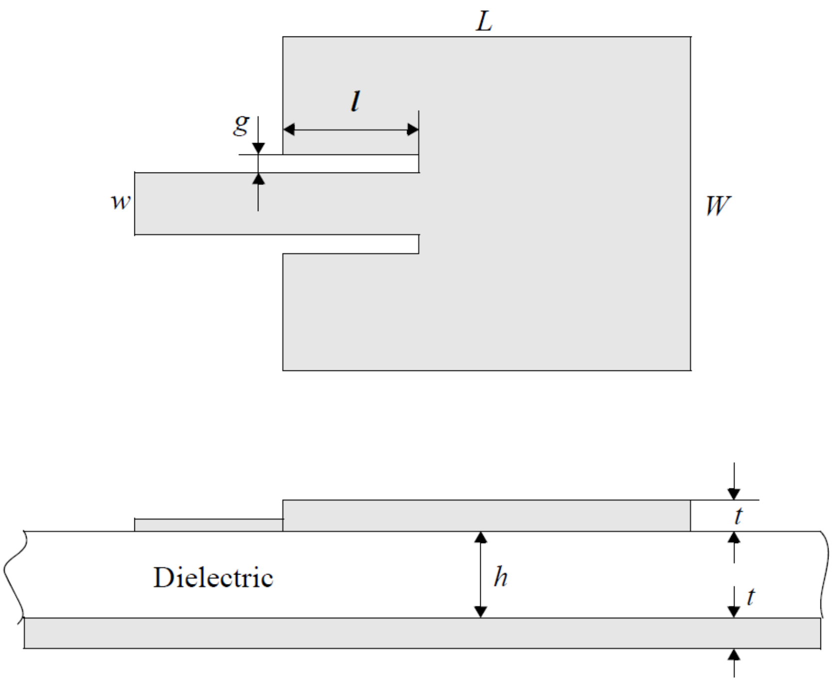

Figure no. 10 – *Usual matching technique of patch antenna with microstrip feeding line*

When a microstrip line is used as a feeding line the layout presented in figure no. 10 is used for a matched connection with the antenna. The length l is computed based on the electrical parameters of the materials and the working frequency.

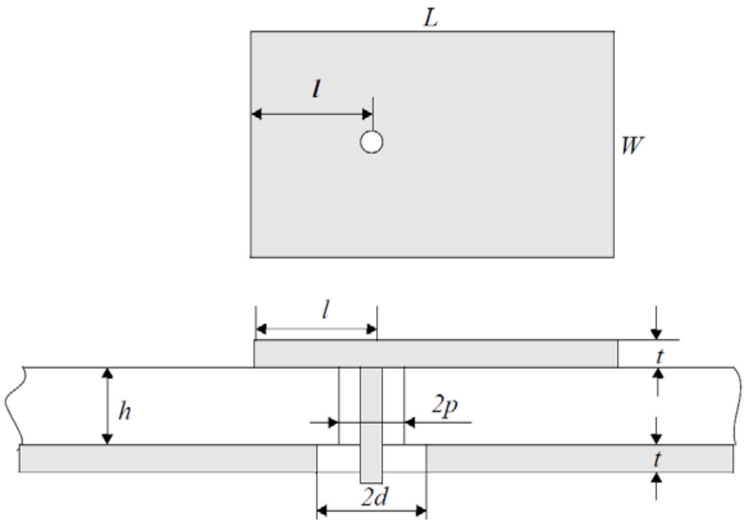

Figure no. 11 – *Point feeding matching technique*

When an external feeding line is used, it could be connected to the antenna at the computed distance from the input edge through an appropriate gap in the dielectric and the ground plane (figure no. 11). This feeding solution allows for increasing the patch antenna radiation efficiency because its input edge is completely free and it radiates along all antenna width.

Radiation Pattern

The two equivalent radiating slots of a patch antenna could be viewed as an array of two antennas distributed along the *Ox* axis of a Cartesian coordinate system (see figure no. 8). For $L = \lambda/2$ (usual case) the slots are fed with in-phase fields. So, the array factor is:

$$f(\theta, \phi) = \cos\left(\frac{k_0 L}{2}\cos\phi\right) \tag{34}$$

The total field radiated by the patch antenna is given by the multiplication of the array factor (34) by the field radiated by an equivalent slot (31 or 32). The obtained result is valid for a free space array of the two slots, which is not true for this case: they are included in a dielectric. Correction factors should be applied. They are computed with the following formulas:

-in *xOy* plane:
$$F(\phi) = \frac{2\tan[\beta_1(\phi)h]\cos\phi}{\tan[\beta_1(\phi)h] - j\varepsilon_r\cos\phi/n_1(\phi)} \tag{35}$$

-in *xOz* plane:
$$G(\theta) = \frac{2\tan[\beta_1(\theta)h]}{\tan[\beta_1(\theta)h] - jn_1(\theta)/(\mu_r\cos\theta)} \tag{36}$$

In the above relations: $\beta_1(x) \triangleq k_0 n_1(x)$, $n_1(x) \triangleq \sqrt{\eta_1^2 - (\sin x)^2}$, $\eta_1 \triangleq \sqrt{\varepsilon_r \mu_r}$.

A patch antenna with $L = \lambda/2$ has a radiation pattern consisting in single lobe perpendicular to the antenna (along *Oz* axis).

Patch Antenna Design

Microstrip antennas come in various shapes and dimensions, but most of them are rectangular or circular and are denoted as patch antennas. The following design notes refer only to patch antennas.

Choosing Dielectric Substrate

The dielectric substrate influences the patch antenna parameters through its relative dielectric constant ε_r and its loss tangent $\tan\delta$. Big values of ε_r allows for small antenna dimensions, but its bandwidth is small, too. A general rule is to use a dielectric with the smallest possible ε_r that allows for fitting the space available for the antenna and, thus, obtaining the biggest possible bandwidth.

Obviously, the patch antenna loss is small for small values of the dielectric $\tan\delta$. From this point of view, the best dielectric materials are quartz, alumina, and Teflon. But they very expensive and are used only for military equipment. The most used dielectric material for consumer applications is a glass-reinforced epoxy laminate, denoted as FR4 (from Flame Retardant – meaning that it has a great resistance to fire), that comes in many variants depending on the producer. There are also proprietary materials developed by main companies in the field.

First choice a patch antenna designer should make is about the dielectric material for the substrate and this is mainly based on the cost. Also, the height *h* of the dielectric sheet is to be established and this is based on the available space and on a possible requirement for the antenna to bend (flexible antenna). The dielectric maximum height h is limited by the requirement of not allowing for exciting of parasitic vertical mode propagation:

$$h \leq \frac{0.3c}{2\pi f_{max}\sqrt{\varepsilon_r}} \qquad (37)$$

where *c* is the free space light velocity and f_{max} is the maximum operating frequency. When *h* increases the bandwidth increases, too, while the dielectric loss decreases.

The next choice is the feeding technique. Options are: microstrip line on the same side, with or without matching, and an external feeding line connected form the opposite side through a hole in the ground conducting plane and in the dielectric. The first technique is technologically easier, but could induce an important blocking of the radiating input edge and reduced antenna radiation efficiency. The second technique brings better radiation efficiency by allowing radiation through the whole input edge, but is technologically more complex.

As for the matching technique one should keep in mind that there are not accurate design formulas nor for the gap *g* between the microstrip line and the antenna (figure no. 10), neither for the hole diameters 2*p* / 2*d* (figure no. 11).

Empirically, the value of *g* is chosen as 10% to 50% from the microstrip line width *w*, with big values of this percent for small values of *w*. The rationale of this choice is that foe small values of *w* the field lines' field bending is greater and they occupy a greater region outside the microstrip line. This extension region should not include parts of the antenna, because they modify the distribution field along the antenna and its radiation pattern. The presence of gap *g* slightly influences the antenna resonance frequency (under 1%), but greatly modify the antenna input impedance. For instance, for $g = w$ the input impedance decreases by 60%.

The antenna length L is chosen such that the resonance condition is met and the antenna input impedance is purely resistive at the operating frequency. Usually it results between 48% and 49% from the wavelength in the dielectric (the ideal condition is $L = \lambda/2$).

The antenna width *W* is strongly dependent on the available space and results between 0.5*L* and 2*L*. A value as big as possible is chosen, because for big values of *W* the antenna input impedance and the ratio *w/W* are small, thus potential high radiation efficiency is obtained. But the antenna width *W* should not be greater than the wavelength, because a parasitic propagation mode along the antenna width is excited and the radiation efficiency decreases.

Work no. 1

General Design of Patch Antenna

General parameters of patch antenna are determined by means of the software program PATCHD. After launching the program asks for the input design data.

1. The shape of the patch antenna: *rectangular* or *circular*:

Do rectangular (r) or circular (c) patch ?

In this laboratory work we study the rectangular patch antenna, so the answer is always r.

2. Operating frequency:

Input antenna frequency (GHz) ?

3. Electrical parameters of the dielectric substrate:

Input substrate relative dielectric constant and loss tangent ?

The values of the two parameters are introduced in the specified order and are separated by comma.

The accepted values for ε_r are between 1 (because all dielectric materials have electrical permittivity greater than the one of the free space, hence $\varepsilon_r > 1$) and 10 (because there were not dielectric materials with $\varepsilon_r > 10$ at the time of program writing). If values outside this interval are introduced, the program issues a WARNING message and asks for change. Answering YES (y) makes the program to reiterate the above question and the values of both of the parameters should be introduced again. Answering NO (n) makes the program to continue with the next question, but the results obtained for $\varepsilon_r < 1$ are not realistic.

If only one numerical value is introduced or the values are not separated by a comma the program issues a WARNING (Redo from start !) and it waits for a syntactically correct answer.

The influence of the loss tangent on the general parameters of antenna is small, so the answer for the loss tangent is always 0.0001.

4. For rectangular patch antenna the next question is issued and it regards the shape factor of the rectangle: if it is a square ($W = L$) or not ($W \neq L$):

Do square (s) or rectangular (r) patch ?

If the answer is s the program skips the next question (no. 5) because it will assign to W the value that it computes for L.

This laboratory work aims at finding general parameters of the patch antenna and we are not interested in specific dimensions, so the answer is always s.

If the answer is r the program asks for:

5. Antenna width W:

Input patch width (cm) ?

The program checks for the introduced value to verify the requirement $0.9 \leq W \leq 2L$. If the check fails the program issues a WARNING message and the question about changing the value of W. If the answer is YES (y) the program waits for the new value to be introduced. If the answer is NO (n) the program continues running, but the obtained results are not realistic.

6. The height of the dielectric substrate (*h*):

Input substrate height (cm) ?

This parameter should be greater than 0.2 cm from technological point of view and smaller than $16\lambda_0^2/(\varepsilon_r - 1)$ in order to minimize the level of the surface wave. A WARNING message is issued if the above conditions are not met, but the program continues running if the user does not want to modify the value initially introduced.

7. The conductivity of the conducting material as compared to that of the copper:

Input conductor conductivity relative to copper ?

The answer should be 1 if copper is used; the ratio between the conductivity of the used material and the one of the copper should be introduced, otherwise.
In this laboratory work the answer is always 1.

8. The acceptable value for the standing wave ratio:

Input acceptable swr for bandwidth calculation ?

This parameter is used for the evaluation of the antenna bandwidth and usually it has a value of 2:1 is accepted; *so, the answer is always 2.*

9. The location of the connection between the microstrip feeding line and the antenna (*l*):

Input feed location (cm) ?

This parameter is used to match the patch antenna with the microstrip feeding line.
This laboratory work aims at finding general parameters of the patch antenna and we are not interested in meeting the matching condition, so the answer is always 0.

The program outputs the following results:

a) Input data.
b) Input impedance at the resonance.
c) Q factor.
d) Efficiency – defined as the ratio of the radiated power to the sum of the radiated power and the surface wave power; it is an indirect measure of the level of the undesired surface wave.
e) Global efficiency – defined as the ratio of the radiated power to the input power; this parameter takes into account the loss in the conducting parts of the antenna and in the dielectric, besides the loss due to the surface wave.
f) Frequency bandwidth – as percent from the operating frequency.

Finally, the following questions are issued:

Print out results (y or n) ?

Store results in a file (y or n) ?

Do another case (y or n) ?

The answers are obvious.

Working Notes

A. *Fill the data in the following table for 3 values of the dielectric height h: h = 0.01 cm, h = 0.02 cm, and h = 0.03 cm, respectively.* (*3 separate tables*)

h =	$\varepsilon_r = 3$	$\varepsilon_r = 6$	$\varepsilon_r = 9$
f =4 GHz	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)
f = 6 GHz	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)
f = 8 GHz	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)	Length (*L*) Efficiency (η) Global efficiency (η_g) Bandwidth *B*(%)

B. *Based on the above data trace the following curves:*

- *B*(MHz) = f(frequency) for ε_r = constant and *h* = 0.02 cm (3 curves on the same diagram)
- L(cm) = f(frequency) for ε_r = constant and *h* = 0.02 cm (3 curves on the same diagram)
- η, ηg = f(frequency) for ε_r = constant and *h* = 0.02 cm (6 curves on the same diagram)
- *B*(MHz) = f(*h*) for constant frequency and ε_r = 6 (3 curves on the same diagram)
- *L*(cm) = f(*h*) for constant frequency and ε_r = 6 (3 curves on the same diagram)
- η, ηg = f(*h*) for constant frequency and şi ε_r = 6 (6 curves on the same diagram)

C. *Answer to the following questions:*

1. What is the minimum bandwidth *B* (in MHz) and what is the simulation parameters combination that yields it ?
2. What is the maximum bandwidth *B* (in MHz) and what is the simulation parameters combination that yields it ?

Work no. 2

Complete Design of Patch Antenna

When designing patch antenna its feeding circuit should be taken into consideration and evaluation of its input impedance should be made in order to determine the actual value of the resonant frequency, which is the frequency that yields a zero value for the input reactance. The complete design of patch antenna is made by running the program PATCH9.

After launching the program asks for a choice to be made by the user:

Do design (d) or analysis (a) ?

The first choice means that the program computes the dimensions of the antenna and evaluates its parameters, while the latter means that the user fetch in the antenna dimensions and the electric parameters of the dielectric and the program computes the antenna parameters.

This work is aimed at designing of patch antenna, so the answer is always d.

Then the following input parameters should be successively entered:

1. Input design frequency in GHz ?

2. Input relative dielectric constant ?

3. Input loss tangent ?

This parameter has a small influence on the antenna dimensions, so we use one single typical value for it in this work: 0.0001.

4. Input substrate height (cm) ?

This parameter has a small influence on the antenna dimensions, so we use one single typical value for it in this work: 0.04 cm.

For some combination of the input parameters it is possible for the program to issue a WARNING message regarding a possible too big value for the substrate height (the program checks for the requirement: $h < 0.001\lambda$ *to be fulfilled). Please ignore the message* !

5. Input line thickness (cm) ? *Recommended value:* 0.00356 cm.

6. Input line conductivity relative to copper ? *Recommended value:* 1

The program computes the length of the patch antenna based on the above input parameters. It makes a number of at most 100 iterations. At each iteration it evaluates the antenna input impedance for different values of antenna length and it retains the value that yields purely resistive input impedance. The user is asked to input the starting length value, the step of its change, and also the value of the antenna width, because it influences the impedance value. The starting length value is recommended by the program.

7. Input patch length (cm) *Recommended value:* the one estimated by the program.
   Estimated patch length = ?

8. Input patch width (cm) ?

A WARNING message is issued if the entered value is greater than λ. *Please ignore it.*

9. Input feed type: m- microstrip, p- probe, n- none ? *Recommended answer*: n.

10. Input fractional change (%) in patch length for initial search (default 5%) ?
Recommended answer: <ENTER> *(that is, the default value)*

The calculus stops when a value of the patch antenna length for which the input impedance is purely resistive or when the maximum limit of 100 iterations is reached. In the latter case the length value is considered the last used value and the user is asked to accept it or to make a new calculus by modifying the fractional change used at step 10.

Before displaying the results, the program asks for the frequency limits the user wants for the representation of the input impedance on Smith diagram. Unfortunately, this representation is made in DOS and this is not supported by the operating system we use in the laboratory. So the answers to the next questions are arbitrary (the program does not allow the user to skip these steps):

11. Input start and stop frecqs (GHz) for impedance calc. ?
Recommended answer: two numerical values separated by comma.

12. Input number of frequencies ?
Recommended answer: a number from 2 to 5.

Finally the program displays:

a) Input data
b) Output results: antenna length, resonance frequency, input impedance at resonance
c) Input impedance in the frequency domain selected in step 11.

and asks the followings:

Plot results on Smith chart (y or n)? *Recommended answer: n.*

Print out results (y or n) ? *Recommended answer: n*

Store results in a file (y or n) ? *Recommended answer: n*

Do another case (y or n) ?

When answering y the program asks:

Change patch width (w), feed inset (f), or start over (o) ? *Recommended answer: o.*

Working Notes

A. *Fill in the following table for* $\varepsilon_r = 3$, $\varepsilon_r = 6$, $\varepsilon_r = 9$ (3 *separate tables*).

$\varepsilon_r =$	$W = 1.2L$	$W = 1.5L$	$W = 1.8L$
f =4 GHz	Patch length (L) Input impedance (R_{in})	Patch length (L) Input impedance (R_{in})	Patch length (L) Input impedance (R_{in})
f = 6 GHz	Patch length (L) Input impedance (R_{in})	Patch length (L) Input impedance (R_{in})	Patch length (L) Input impedance (R_{in})
f = 8 GHz	Patch length (L) Input impedance (R_{in})	Patch length (L) Input impedance (R_{in})	Patch length (L) Input impedance (R_{in})

In order to compute the value of W, use the estimated value of patch length L suggested by the program at step 7.

B. *Trace on paper the following curves*:

- L = f(frequency) for ε_r = constant and W/L = 1.5 (3 curves on the same diagram)
- R_{in} = f(*W/L*) for *f* = 6 GHz şi ε_r = constant (3 curves on the same diagram)
- R_{in} = f(*W/L*) pentru *f* = constant şi ε_r = 6 (3 curves on the same diagram)

C. *Answer the following questions*:

- What combination of parameters' values yields the minimum value for patch length ?
- Does the patch width influence the input impedance ? How ?
- Compute de half wavelength at the used frequencies. Do they match the patch length computed by the program ? Explain !

Work no. 3

Matching Patch Antenna with its Feeding Line

As we previously said the matching between the patch antenna and its microstrip feeding line is done by means of moving their junction from the input edge (where the patch antenna characteristic impedance is big) towards the patch middle plane, noting that here the patch antenna characteristic impedance is zero and so, there is a plane somewhere between the input edge and the middle plane where the patch antenna characteristic impedance is 50 ohms (supposing that the microstrip feeding line has a characteristic impedance of 50 ohms).

Computing the matching condition consists in computing the distance l from the antenna input edge where the junction between antenna and the microstrip feeding line should be made. This is done by using the program PATCH9.

After launching the program asks for a choice to be made by the user:

Do design (d) or analysis (a) ?

The first choice means that the program computes the dimensions of the antenna and evaluates its parameters, while the latter means that the user fetch in the antenna dimensions and the electric parameters of the dielectric and the program computes the antenna parameters.

This work is aimed at designing of patch antenna, so the answer is always d.

Then the following input parameters should be successively entered:

1. Input design frequency in GHz ?

2. Input relative dielectric constant ?

3. Input loss tangent ?

This parameter has a small influence on the antenna dimensions, so we use one single typical value for it in this work: 0.0001.

4. Input substrate height (cm) ?

This parameter has a small influence on the antenna dimensions, so we use one single typical value for it in this work: 0.02 cm.

For some combination of the input parameters it is possible for the program to issue a WARNING message regarding a possible too big value for the substrate height (the program checks for the requirement: $h < 0.001\lambda$ *to be fulfilled). Please ignore the message* !

5. Input line thickness (cm) ? *Recommended value:* 0.00356 cm.

6. Input line conductivity relative to copper ? *Recommended value:* 1

The program computes the length of the patch antenna based on the above input parameters. It makes a number of at most 100 iterations. At each iteration it evaluates the antenna input impedance for different values of antenna length and it retains the value that yields purely resistive input impedance. The user is asked to input the starting length value, the step of its change, and also the value of the antenna width, because it influences the impedance value. The starting length value is recommended by the program.

7. Input patch length (cm) *Recommended value:* the one estimated by the program.
   Estimated patch length = ?

8. Input patch width (cm) ?

A WARNING message is issued if the entered value is greater than λ. Please ignore it.

9. Input feed type: m- microstrip, p- probe, n- none ? *Recommended answer*: m.

10. Input feed point distance wrt to patch edge <cm> ? *Recommended answer*: 0

11. Input feed line width <cm> ? *Recommended answer*: W/5. (*W is the value introduced at step 8*).

12. Input fractional change (%) in patch length for initial search (default 5%) ?
    Recommended answer: <ENTER> *(that is, the default value)*

The calculus stops when a value of the patch antenna length for which the input impedance is purely resistive or when the maximum limit of 100 iterations is reached. In the latter case the length value is considered the last used value and the user is asked to accept it or to make a new calculus by modifying the fractional change used at step 10.

Before displaying the results, the program asks for the frequency limits the user wants for the representation of the input impedance on Smith diagram. Unfortunately, this representation is made in DOS and this is not supported by the operating system we use in the laboratory. So the answers to the next questions are arbitrary (the program does not allow the user to skip these steps):

13. Input start and stop frecqs (GHz) for impedance calc. ?
    Recommended answer: two numerical values separated by comma.

14. Input number of frequencies ?
    Recommended answer: a number from 2 to 5.

Finally the program displays:

d) Input data
e) Output results: antenna length, resonance frequency, input impedance at resonance
f) Input impedance in the frequency domain selected in step 11.

and asks the followings:

Plot results on Smith chart (y or n)? *Recommended answer: n.*

Print out results (y or n) ? *Recommended answer: n*

Store results in a file (y or n) ? *Recommended answer: n*

Do another case (y or n) ?

When answering y the program asks:

Change patch width (w), feed inset (f), or start over (o) ?

Recommended answer is explained in the working notes.

Working Notes

A. *Fill in the following tables*:

$\varepsilon_r = 3$	*W* = 2 cm	*W* = 2,4 cm	*W* = 2,8 cm
f = 4 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=
f = 5 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=
f = 6 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=

$\varepsilon_r = 5$	*W* = 1,6 cm	*W* = 1,8 cm	*W* = 2 cm
f = 4 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=
f = 5 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=
f = 6 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=

$\varepsilon_r = 7$	*W* = 1,4 cm	*W* = 1,6 cm	*W* = 1,8 cm
f = 4 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=
f = 5 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=
f = 6 GHz	*L*=	*L*=	*L*=
	l=	*l*=	*l*=
	l/L=	*l/L*=	*l/L*=

Note that for a pair (*f*, *W*) you have to fill 3 values: patch length *L* and feed inset *l* – displayed by the program and also the ratio *l/L* – computed after finalizing all the simulations. The value of *l* is the one obtained after successive simulations answering with f to the question:

Change patch width (w), feed inset (f), or start over (o) ?

until a value of 50 ohms is obtained for the input impedance (any value between 49.5 and 50.5 is considered a good approximate for 50 !).

In order to pass to another pair (*f*, *W*) on the same line of the table you have to answer with w to the above question.

In order to pass to another pair (*f*, *W*) on the other line of the table you have to answer with o to the above question.

B. *Trace the curves l/L = f(W) for constant frequency, for each of the tables (1 diagram containing 3 curves, for each of the tables).*

C. *Answer the following questions*:

- What combination of parameters' values yields the minimum value for *l* ?
- What combination of parameters' values yields the minimum value for *l/L* ?

Work no. 4

Design of Shorted Patch Antenna

As we showed previously there is a standing wave regime for the electromagnetic field in the dielectric of patch antenna due to the total reflection produced at the open circuit termination at the antenna edge opposite to the input. For usually used patch antenna with $L = \lambda/2$ this means a maximum value of field at the input edge a monotonically decreasing to zero in the middle plane followed by a monotonically increase to a maximum at the output edge. The voltage along the antenna length follows the same variation law.

For applications offering a very limited space for antenna, length size should be smaller than $\lambda/2$, but the resonance condition should be fulfilled in order to have a resistive only input impedance. For these applications the patch length is limited to $\lambda/4$ and the field distribution is preserved by artificially grounding the output edge through metallic pins connected between the antenna and the ground plane (figure no. 12). This is the shorted patch antenna.

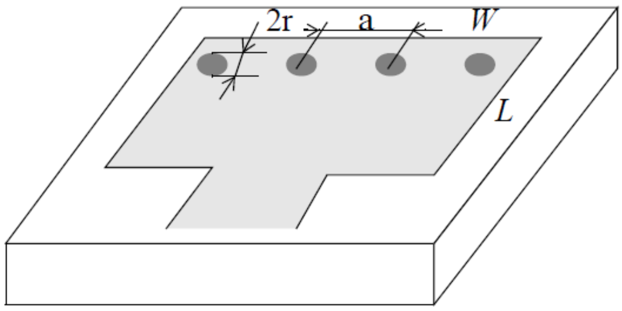

Figure no. 12 – *Shorted patch antenna*

The grounding pins are not perfect resistors, but they exhibit a small reactance. To compensate for it, the patch length should be slightly greater than $\lambda/4$.

The program SCPATCH computes the shorted patch antenna length by using a circuit model for the grounding pins with diameter 2*r* and uniformly spaced at *a* centimeters.

After launching the program asks for a choice to be made by the user:

Do design (d) or analysis (a) ?

The first choice means that the program computes the dimensions of the antenna and evaluates its parameters, while the latter means that the user fetch in the antenna dimensions and the electric parameters of the dielectric and the program computes the antenna parameters.

This work is aimed at designing of shorted patch antenna, so the answer is always d.

Then the following input parameters should be successively entered:

1. Input design frequency in GHz ?

2. Input relative dielectric constant ?

3. Input loss tangent ?

This parameter has a small influence on the antenna dimensions, so we use one single typical value for it in this work: 0.0001.

4. Input substrate height (cm) ?

This parameter has a small influence on the antenna dimensions, so we use one single typical value for it in this work: 0.03 cm.

For some combination of the input parameters it is possible for the program to issue a WARNING message regarding a possible too big value for the substrate height (the program checks for the requirement: $h < 0.001\lambda$ *to be fulfilled). Please ignore the message* !

5. Input line thickness (cm) ? *Recommended value:* 0.00356 cm.

6. Input line conductivity relative to copper ? *Recommended value:* 1

The program computes the length of the shorted patch antenna based on the above input parameters. It makes a number of at most 100 iterations. At each iteration it evaluates the antenna input impedance for different values of antenna length and it retains the value that yields purely resistive input impedance. The user is asked to input the starting length value, the step of its change, and also the value of the antenna width, because it influences the impedance value. The starting length value is recommended by the program.

7. Input patch length (cm) *Recommended value:* the one estimated by the program.
   Estimated patch length = ?

8. Input patch width (cm) ? *Recommended value:* the value estimated at previous step multiplied by 1.5.

A WARNING message is issued if the entered value is greater than λ*. Please ignore it.*

9. Input feed type: m- microstrip, p- probe, n- none ? *Recommended answer*: m.

10. Input feed point distance wrt to patch edge <cm> ? *Recommended answer*: 0

11. Input feed line width <cm> ? *Recommended answer*: W/5. (*W is the value introduced at step 8*).

12. Use shorting pins for short circuit <y or n> ?

This question is somewhat misleading: the shorting pins are always used ! The real meaning of this question is if user wants to include or not a circuit model for the pins. If the answer is n*, the following two steps are skipped because the program considers that the pins are perfect conductors (ideal short circuit).*

13. Input shorting pin diameter <cm>? *Recommended answer*: 0.1

14. Input center-to-center spacing between pins <cm>? *Recommended answer*: 0.3

15. Input fractional change (%) in patch length for initial search (default 5%) ?
    Recommended answer: <ENTER> *(that is, the default value)*

The calculus stops when a value of the patch antenna length for which the input impedance is purely resistive or when the maximum limit of 100 iterations is reached. In the latter case the length value is considered the last used value and the user is asked to accept it or to make a new calculus by modifying the fractional change used at step 10.

Before displaying the results, the program asks for the frequency limits the user wants for the representation of the input impedance on Smith diagram. Unfortunately, this representation is made in DOS and this is not supported by the operating system we use in the laboratory. So the answers to the next questions are arbitrary (the program does not allow the user to skip these steps):

16. Input start and stop frecqs (GHz) for impedance calc. ?
Recommended answer: two numerical values separated by comma.

17. Input number of frequencies ?
Recommended answer: a number from 2 to 5.

Finally the program displays:

g) Input data
h) Output results: antenna length, resonance frequency, input impedance at resonance
i) Input impedance in the frequency domain selected in step 16.

and asks the followings:

Plot results on Smith chart (y or n)? *Recommended answer: n.*

Print out results (y or n) ? *Recommended answer: n*

Store results in a file (y or n) ? *Recommended answer: n*

Do another case (y or n) ?

When answering y the program asks:
Change patch width (w), feed inset (f), or start over (o) ? *Recommended answer: o.*

Working Notes

A. *Fill in the following table with length of the shorted patch antenna for:*

- an ideal short circuit in the output plane (answer with n at the question at step 12):
Use shorting pins for short circuit <y or n> ?

	f = 4 GHz	f = 6 GHz	f = 8 GHz
$\varepsilon_r = 3$	Patch length	Patch length	Patch length
$\varepsilon_r = 6$	Patch length	Patch length	Patch length
$\varepsilon_r = 9$	Patch length	Patch length	Patch length

- a real short circuit in the output plane (answer with y at the question at step 12):
Use shorting pins for short circuit <y or n> ?

	f = 4 GHz	f = 6 GHz	f = 8 GHz
$\varepsilon_r = 3$	Patch length	Patch length	Patch length
$\varepsilon_r = 6$	Patch length	Patch length	Patch length
$\varepsilon_r = 9$	Patch length	Patch length	Patch length

- *Find the shorting ratio η by dividing the values written in the above tables to the ones in the following table, which represent the length of normal patch antenna*:

	f = 4 GHz	f = 6 GHz	f = 8 GHz
$\varepsilon_r = 3$	2,17 cm	1,53 cm	1,23 cm
$\varepsilon_r = 6$	1,44 cm	1,02 cm	0,83 cm
$\varepsilon_r = 9$	1,08 cm	0,76 cm	0,60 cm

B. *Trace the curves*:
- $\eta = \mathrm{f}(\varepsilon_r)$ for constant frequency (6 curves on the same diagram).
- $\eta = \mathrm{f(frequency)}$ for $\varepsilon_r = \mathrm{constant}$ (6 curves on the same diagram).

C. *Answer the following questions*:
- which is the combination of parameters' values that yields the minimum η ?
- what is the ideal value of η ?

Work no. 5

Design of Patch Antenna Linear Array

A linear antenna array is a group of identical antennas placed along a line. Designing a linear antenna array means finding the following parameters:

- number of antennas (denoted as array elements);
- spacing between elements (uniform arrays have the same spacing between any two neighbor elements);
- amplitude of the feeding current of elements (uniform arrays have the same amplitude for all the elements);
- phase shift of the feeding currents (uniform arrays have the same phase shift between any two neighbor elements);

Usually, a designer establishes the type of antenna, the number of elements and their inter spacing based on his experience. The design consists in determining the current amplitudes and the phase shift between neighbor elements in order to meet the design criteria. The main design criteria are: direction and beamwidth of the main lobe, the maximum level of the side lobes, directions of the radiation pattern nulls.

The program APERDIST asks the user to input the parameters that describes the array geometry and the feeding techniques; then it computes the excitation current amplitudes and displays the array radiation pattern (denoted as array factor).

The user has to choose a current distribution law, that is how the excitation current amplitudes vary from an element to another. This law could be uniform or tapered. The first one means that all the amplitudes are the same, while the latter one means that the elements in the array center have the biggest current amplitudes and these amplitudes continuously decreases towards the array ends. The elements at the array edges have the smallest current amplitude and this amplitude is denoted as the distribution pedestal.

The program use normalized current amplitudes, thus the central element has the normalized amplitude 1, while the others have normalized amplitude smaller than 1. The pedestal is expressed in dB. Use of normalized amplitudes for even number of elements is optional.

After launching the program asks the user to enter the following parameters:

1. Input frequency (GHz)

2. Input element spacing (cm)
   [wavelength = cm] *This information is offered by the program in order to help user choosing an acceptable spacing (practically used values are smaller than one wavelength).*
3. Input number of elements
   [maximum number of elements = 50]

4. Number of elements is even.
   Normalize n/2 and (n/2+1) excitations to 1 (y or n) ? *Recommended answer*: y

5. Input desired aperture distribution
   u – uniform
   l – linear taper on a pedestal
   q – quadratic taper on a pedestal
   c – cosine on a pedestal
   s – cosine squared on a pedestal

6. Input edge illumination (in positive dBs) *The pedestal for tapered distributions*

7. Want to calculate radiation pattern (y or n) ? *Recommended answer: y.*

8. Input element to element phase shift (deg)

9. Include element pattern (y or n) ? *Recommended answer: n.*

10. Input start and stop angles for pattern calculation *Recommended answer:* –90, 90
    (broadside = 0 degrees)

11. Input number of angles to be calculated *Recommended answer:* 180

12. The program displays
    Scan angle = xxx degrees *Direction of the main lobe*
    and asks:
    Want to plot pattern (y or n) ? *Recommended answer: y*

13. Rectangular (r) or polar plot (p) ?

14. Input dB ranges [20, 40, 60, 80] for plot *Recommended value:* 20

15. Input angle scale (45, 90, 180) *Recommended value:* 90

Radiation pattern is displayed. It remains on the screen until <ENTER> is pressed.

16. Want to store pattern in a file (y or n) ? *Recommended answer: n*

Input data, modulus and phase of the excitation coefficients are displayed.

17. Print out excitation coefficients (y or n) ? *Recommended answer: n*

18. Do another case (y or n) ?

After answering y:

19. Input option
    Change aperture distribution (d)
    Change number of elements (n)
    Change element spacing (s)
    Start over (o)

Working Notes

1. Using N = 25 elements, 2 cm spacing, 0 degree phase shift, and frequency of 5 GHz determine main lobe beamwidth at –5dB and level of the greatest side lobe for the all 5 aperture distributions (10 dB pedestal). Write data in a table.

2. Using N = 25 elements, 2 cm spacing, 0 degree phase shift, frequency of 5 GHz, and cosine aperture distribution determine main lobe beamwidth at –5dB and level of the greatest side lobe for pedestal values of 5, 10, 15, 20, and 25 dB. Write data in a table.

3. Using N = 25 elements, 0 degree phase shift, frequency of 5 GHz, and quadratic aperture distribution with pedestal of 10 dB determine main lobe beamwidth at –5dB and level of the greatest side lobe for inter element spacing of 1.5, 2, 3, and 4 cm. Write data in a table.

4. Using N = 25 elements, 2 cm spacing, frequency of 5 GHz, and quadratic cosine aperture distribution with pedestal of 10 dB determine main lobe direction and level of the greatest side lobe for phase shift of 15, 30, 45, 60, and 90 degrees. Write data in a table.

5. Using 2 cm spacing, 0 degree phase shift, uniform aperture distribution, and frequency of 5 GHz determine main lobe beamwidth at –5dB and level of the greatest side lobe for N = 20, 30, 40, and 50 elements. Write data in a table.