Abstract — Modeling of patch antennas using the conventional network model produces major discrepancies, in particular, if the patch height is relatively large. In an investigation of a patch antenna of variable height the antenna reflection coefficient was measured and an improved network model was fitted to the measured data. It turned out that in order to achieve the best fit, the conventional model has to be complemented by a series resistor in the feed section which is shown to represent radiation from the probe. Dependence of radiation resistance on patch height is such that the probe can be modeled as a Hertzian monopole over ground.

I. INTRODUCTION

Patch antennas have been used for decades as simple and inexpensive antenna elements fabricated on dielectric printed circuit boards. The understanding of the impedance and the radiation properties is well supported by a simple network model presented in many textbooks [1], [2] using a transmission line equivalent for the patch and representing the radiation by (slot radiator-) conductances terminating the transmission line. Probe coupling of the patch to a coaxial transmission line from behind the ground plane is successfully modeled by an inductor. As is well known, the impedance match bandwidth of patch antennas is too low for many applications and is limited mainly by the height of the patch over ground. However, when patch antennas of large height are investigated, it is found that the simple network model described above no longer works satisfactory: Both the radiation pattern degrades and the reflection coefficient plot deviates from the model prediction.

In an investigation aimed at analyzing the broadbanding technique of series resonant compensation of the probe inductance, the reflection coefficient of a patch antenna of variable height was measured and an extended network model was fitted to the measured data. The result gave new insight into the radiation mechanism and allows better design of wide bandwidth patch antennas.

II. CONVENTIONAL MODEL

The patch antenna under consideration is shown in Fig. 1. The patch is a solid plate of brass which is kept in place at variable height over the ground plane by a plastic screw in the center position of the patch. The patch is fed by a probe from an SMA coaxial plug mounted to the back of the ground plane; the probe is the center conductor of the coaxial transmission line. The reflection coefficient was measured for heights between 3% and 10% wavelength at resonance frequency around 1 GHz (h = 10mm, 18mm, 25mm and 30mm) as shown in Fig.2. It is seen that the resonance loop shift due to a series inductance progresses with increasing height and that the loop diameter decreases and the distance of the loop from the periphery of the smith chart (r = 1) increases at the same time.

The measurements were first fitted to a conventional network model as shown in Fig.3. It is seen from the schematic that the patch is represented by two sections of microstrip line (MLIN) and that the end effect is modeled by a microstrip gap (MGAP) to represent the end capacitance and a resistance to ground (ZIP) to represent the patch edge radiation. The terminal (Term) is connected via the inductor (L) to the interconnection of the two microstrip transmission line sections and a capacitor C1 represents the stray electric field at the transition from the coaxial transmission line to the inductive probe.
We can fit the network model to the measured data (with highest weight around resonance) by letting the simulation tool vary the capacitance, the length of the two sections of microstrip line and the edge radiation resistance. When we compare the reflection coefficients of the model and the measurement in Fig. 3(b), we find that above resonance frequency the simulated reflection coefficient magnitude is too large (close to the Smith Chart outer circle) and at lower frequencies the reflection coefficient magnitude falls off contrary to the measurement.

This exercise was done for all measurements (patch height varied) and equally close fit was achieved in all cases and produced results for the series resistance and inductance of the probe as a function of probe length.

**IV. DISCUSSION OF MODEL PARAMETERS**

Resistance values of the new series resistor as a function of patch height exhibit characteristic height dependence, see Fig. 5:

Due to the high resistance values and the close to quadratic dependence with patch height, the newly introduced series resistor probably does not represent conductor losses; at least we can conclude this from considering the probe resistance (resistance including skin effect would yield far below 1Ω) and a check on efficiency (a preliminary Wheeler-cap measurement exhibited about 95% efficiency).
A possible explanation could be radiation resistance of the probe: To check this assumption we model the probe as a Hertzian monopole over ground, with constant current distribution along its length, as shown in Fig.6.

![Fig.6: The patch antenna probe interpreted as a Hertzian dipole](image)

The radiation resistance of a Hertzian dipole over conducting ground is calculated as half the resistance of a (double-length) Hertzian radiator in free space

$$R = \frac{1}{2} \cdot 790\Omega \cdot \left(\frac{L}{\lambda}\right)^2$$  \hspace{1cm} (1)

where $L$ is $2 \cdot h$.

E.g., with the patch height over ground $h=25$ mm ($h/\lambda = 0.08$) the radiation resistance $R$ at 1 GHz becomes about $10\,\Omega$.

From Fig.5 we see a close agreement of the model series resistance points with our theoretical Hertzian monopole model, which supports our assumption concerning the nature of the resistive series component in the network equivalent.

A further support comes from the strong un-symmetry in the E-plane radiation pattern, Fig.7.

![Fig.5: Resistance of series resistor as a function of patch height $h$; red line for Hertzian monopole](image)

![Fig.7: Measured patch radiation patterns](image)

This degradation can be explained by superposition of fields from the patch edge slot radiators and the un-symmetrically positioned vertical probe while both have the same polarization in that plane; in H-plane the probe radiation is cross-polarized so that the co-polar pattern remains undisturbed.

On the other hand, the series inductance which models the probe exhibits a proportional increase with probe length (equal to patch height), as seen in Fig.8. The proportionality constant conforms closely to constant $K_4$ in the approximate formula for a straight wire in free space of 1.3mm diameter [3].

![Fig.8: Inductance of probe as a function of patch height; red line for isolated conductor inductance](image)

This behavior also supports the assumption of uniform current distribution along the probe length which is essential to the Hertzian monopole model of probe radiation.

Finally, improved tracking of the network model reflection coefficient and measured data for frequencies below and above the resonance range could only be achieved by giving the series resistance the frequency dependence due to (1) and in addition giving the patch edge slot radiation resistance (the inverse radiation
conduction) the inverse variation proportional to \((1/f)^2\) which we may assume in principle due to the single slot radiation conductance approximation for hemispherical radiation

\[
G \approx \frac{1}{90\Omega} \left( \frac{w_{\text{eff}}}{\lambda} \right)^2
\]

where \(w_{\text{eff}}\) is the effective width of the slot radiator, equivalent to the effective width of the microstrip line.

Modeling the edge slot as an isolated slot neglects the mutual coupling effect. Mutual coupling, however, is accounted for at first order by the fitting procedure where the best fit radiation conductance is searched and found. Never-the-less, as seen from Fig.4(b), there still is a considerable deviation visible at low frequencies which requires that the radiation conductances in our model decay even more with frequency than predicted by eq. (2). The mechanism behind this decay is the phase relationship of the edge fields which follows from transmission line theory: At resonant frequency, the transmission line is half-wavelength so that the two edge voltages are at opposite polarization and the slot radiator fields therefore are in-phase; at very low frequencies, the two edge voltages are at equal phase which means the slot radiators are anti-phase, thus canceling radiation and leading to zero radiation conductance. Including a suitable transmission line factor in the variable expression for the edge slot radiation resistance of our network model thus produces better fit of model and measured data at the low-end frequency range, as seen in Fig.9:

V. APPLICATION

The network model can be used to precisely predict the effect of compensation techniques used to match and broaden the patch antenna input impedance. An example is shown in Fig.10(a), where we see the patch antenna of 25mm height with a series capacitor to compensate the series inductance by series resonance.

![Fig.10(a): Patch antenna of 25mm height using series capacitor compensation](image)

The measured reflection coefficient compares well with the simulation result using the network model of the patch antenna without modifications in the patch and probe structure and applying the best-fit capacitance \((C_s = 14.5\text{nF})\), as seen in Fig.10(b):

![Fig.10(b): Simulated (blue) and measured (red) reflection coefficient of patch antenna of 25mm height using series capacitor compensation](image)

III. CONCLUSION

Applying and extending the transmission line model of the patch antenna to include the frequency dependence of radiation resistances we have noticed that the probe has to be modeled as an inductor with a resistance in series. Based on the achieved high accuracy fitting of measured data and model simulations for patch antennas of variable height it was found that the series resistance conforms closely to the theoretical radiation resistance of a Hertzian monopole. Thus we conclude that the probe acts as an independent radiator of the top-loaded monopole type superimposing the ordinary patch radiation which also explains the un-symmetric E-plane radiation pattern of the patch antenna.

REFERENCES