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DESIGN, FABRICATION, AND MEASUREMENT OF A ONE-DIMENSIONAL PERIODICALLY STRUCTURED SURFACE ANTENNA

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Abstract**—**A radiating periodically structured surface resonator is studied from the point of view of minimizing the radiation Q-factor of the fundamental mode of the resonator. Structures with a one-dimensional array of gaps are considered, where the resonant mode is formed by the capacitance of the gaps resonating with the inductance of the conducting pathways. An eigenmode study of a range of designs of identical size demonstrates that increasing the number of gaps does not lower the Q. The results show that this family of resonators has a radiation Q that is typically ~2× lower than a simple patch antenna occupying the same electrical volume. The improvement in Q is accompanied by a corresponding reduction in the directivity gain of the broadside radiation, confirming the inherent bandwidth/directivity trade-off in radiators of identical size and shape. A three-period resonator is made into an antenna by driving it from underneath the surface. The fabricated antenna has dimensions of $0.40\lambda \times 0.26\lambda$ a , a thickness of $\lambda/35$, and a measured 10 dB return loss bandwidth of 12.4%, ~4.5× wider than a simple patch antenna of the same size. These antennas can replace patch antennas in applications demanding the widest possible impedance bandwidth from a thin antenna.

Index Terms**—**Periodic structures, Q-factor, resonant antennas.

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I. INTRODUCTION

It is well known that the bandwidth of a patch antenna decreases as the thickness of the patch is made smaller [1]. For many applications, it is desirable to have an antenna with the radiation characteristics of a patch (horizontally polarized broadside emission off an extended ground plane) with as low a profile as possible (minimal thickness). Whether or not the patch antenna represents a bandwidth-optimized solution to this problem is not clear. When exploring alternatives to the patch antenna, it is important to compare not only the performance of the full antenna designs, but also the physical properties of the resonant modes of the alternative structures directly with those of the patch. A direct comparison of the resonant modes enables the physical origin of any bandwidth improvements to be clearly revealed. In this paper, we study a periodically structured surface resonator that is used to provide a wider bandwidth alternative to a simple patch antenna with a thickness of less than 1/30 of a wavelength. The bandwidth improvement results, in part, because the resonator has a fundamental radiation mode with a lower radiation Q-factor than the simple patch of the same electrical volume. The lower Q is accompanied by a lower broadside directivity gain, revealing the inherent bandwidth/directivity trade-off in structures of identical size and shape. This tradeoff may be acceptable for applications demanding the widest possible impedance bandwidth from a thin antenna, and desirable for applications requiring a wider beam width.

We first present the results of a Q-factor study comparing the fundamental radiation modes of various resonator structures to those of identically-sized patch antennas. One example of the periodic surface resonator is then fabricated into an impedance-matched antenna. Separating the resonator design problem from the impedance matching problem enables a rapid comparison of a wide range of structures and provides additional physical insight into the mechanisms affecting performance. The impedance matching problem need only be solved on the optimized resonator structure.

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II. RESONATOR DESIGN AND Q-FACTOR STUDY

The periodically structured resonator considered here is illustrated in Fig. 1. For all cases studied, the resonator has dimensions of 38 × 60 mm, with a height of 4 mm, and sits on a large ground plane. The top surface of this structure is covered with a conductor, and at the two edges of the 60 mm length the conductor is folded down and connected to ground. The top surface of the resonator has a periodic array of gaps, and Fig. 1(a)–(c) illustrate examples of one-, three-, and five-period resonators. The space inside the resonator can be air, or can be partially or completely filled with a dielectric material. We consider here the case of a thin dielectric layer suspended just underneath the top surface (in the experimental realization, this is the printed circuit board onto which the periodic pattern is printed), and the underlying space is air. For the case of a resonator with no gaps there is a cavity resonance at the frequency where the resonator is a half wavelength (2500 MHz). Adding a 0.64 mm substrate layer with a dielectric constant of 10.2 to the underside of the cavity surface lowers the cavity resonance to 2265 MHz (the radiation Q-factor of the mode at this frequency is 33.6). The electric field of the basic cavity mode is illustrated in Fig. 2(a).

If we introduce a single gap of 8mm width at the center of the top surface (creating a one-period resonator), we find two resonant modes in the new structure. The first mode, illustrated in Fig. 2(b), is a modified version of the cavity mode of Fig. 2(a); it has a slightly higher resonant frequency of 2313 MHz, and a radiation Q-factor of 30.7. The second mode of the one-period resonator is illustrated in Fig. 2(c). This mode

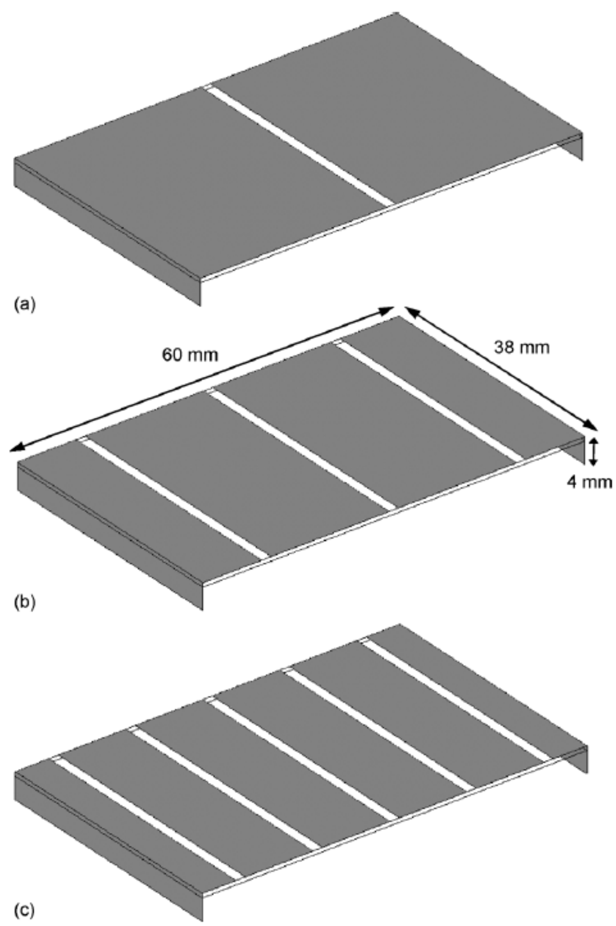

Fig. 1. (a) The one-period periodic surface resonator (the underlying ground plane is not shown). (b) The three-period resonator, with the dimensions indicated (the same dimensions are used in all of the resonators discussed here). (c) The five period resonator.

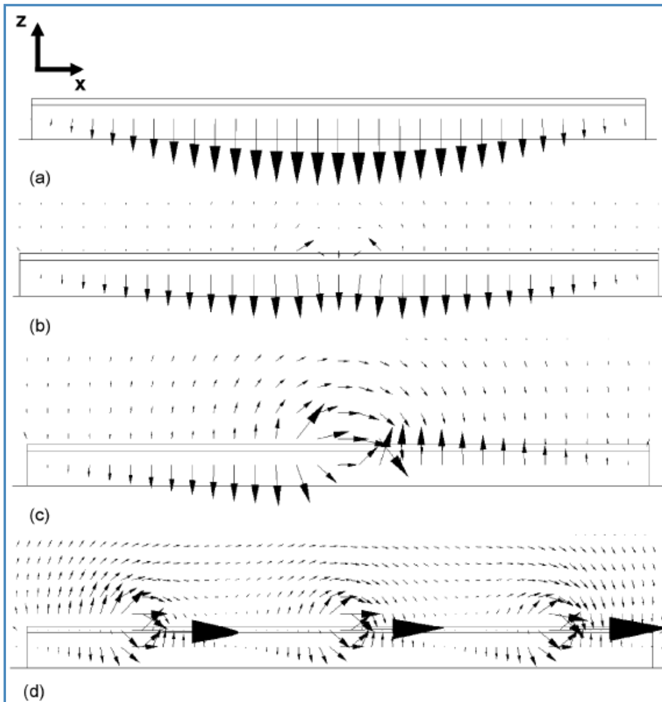

Fig. 2. The electric field for the resonant modes of several structures. (a) The cavity mode of the resonator with no surface gaps, which occurs at the frequency where the cavity length is $\lambda/2$. (b) The modified cavity mode of the one-period resonator, which is nearly identical to the mode in (a). This is not the mode that will be used for radiation. (c) The fundamental radiation mode of the oneperiod resonator, which appears at a lower frequency and has a lower Q than the modified cavity mode. The resonant frequency of this mode is formed by the gap capacitance resonating with the inductance of the conducting pathways to ground. (d) The fundamental radiation mode of the three-period resonator.

is different in structure from the cavity mode, and shows notably improved coupling to radiation. The mode has a resonant frequency of 1865 MHz, and a much lower -factor of 16.0. It is characterized by a strong x-directed field in the gap region, and inside the cavity the z-directed component displays opposite polarities about the center. The magnitude of the electric field is plotted on a logarithmic scale in Fig. 3(a) to illustrate the modal field pattern in detail.

One interesting aspect of the low-*Q* mode of Fig. 2(c) is that its resonant frequency can be varied over a wide range by simply varying the width of the gap at the center of the top surface. Reducing the gap size from 8 mm to 0.75 mm, for example, moves the resonant frequency from 1865 MHz to 1053 MHz, whereas the cavity mode corresponding to Fig. 2(b) remains close to 2265 MHz. This makes sense based upon the electric field profiles: the cavity mode has a very small field inside the gap, and is relatively insensitive to variations in gap size; its resonant frequency is determined by the half-wavelength cavity criterion. The low frequency mode, by contrast, is formed by the gap capacitance resonating with the inductance of the conducting pathway to ground; this resonance is moved to lower frequencies by increasing the gap capacitance (either by reducing the gap size, or by increasing the permittivity or thickness of the substrate layer underneath the gap). One consequence of moving the resonance to much lower frequencies is that its radiation *Q*-factor increases to *Q*=72. This is expected because the physical size of the resonator has not changed; its electrical size is therefore much smaller at the lower resonant frequency and the *Q* must be higher.

Similar behavior is observed in the three-period and five-period resonators of Fig. 1(b) and (c). In a three-period resonator with identical overall dimensions (38 60 4 mm), using a gap size of 0.75 mm and a 0.64 mm substrate with permittivity 10.2 just underneath the top surface, the low-*Q* resonant mode is found at 1970 MHz with a *Q*=15.7. Although the gap size and substrate parameters are identical to the one-period case, the three-period resonator has three gap capacitances wired in series, resulting in 1/3 the overall capacitance, yielding a higher resonant frequency (the inductance is reduced slightly as well, due to the currents going to zero at three points along the surface rather than one). The electric field profile of this mode is shown in Fig. 2(d). The mode is characterized by strong in-phase and equal magnitude -directed electric fields in the three gap regions. The magnitude of the electric field is shown on a logarithmic scale in Fig. 3(b) to illustrate the detailed structure of the mode. In each region of the cavity underneath a gap, the mode shows a structure similar to that seen in the one-period resonator, with this pattern now repeated three times. Likewise, in the five-period resonator mode [see Fig. 3(c)] the pattern is repeated five times, with in-phase equal magnitude x-directed electric fields in each of the five gaps. For the three-period resonator, there is also a modified cavity resonance similar in structure to the basic cavity mode of Fig. 2(a), but this mode appears at 2941 MHz (well above the half wavelength frequency of 2500 MHz) and has a

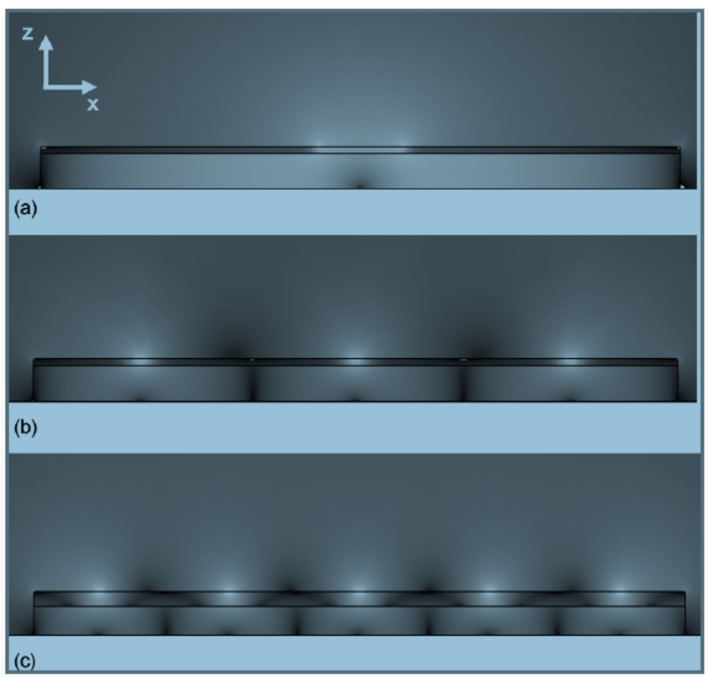

Fig. 3. The magnitude of the electric field for the fundamental radiation mode of the (a) one period, (b) three period, and (c) five period resonators. The field is plotted on a logarithmic scale with the lighter regions representing areas of higher magnitude.

Q=26.3. For the five-period resonator example illustrated in Fig. 3(d), the overall dimensions remain identical, the gap size is reduced to 0.5 mm and a 1.28 mm substrate with permittivity of 20 is used to increase the capacitance; this results in a resonant mode at 1589 MHz with a Q=*28.8*. The higher modified cavity mode for this example is found at 2580 MHz with Q=47.7.

In order to assess the performance of these resonators as potential antenna elements, the Q-factor must be evaluated for a range of designs. A comparison of among Q different designs is complicated by the fact that the Q will naturally increase as the electrical size of the resonator is made smaller. In order to compare designs of different electrical size, we plot Q versus resonant frequency for a wide range of design variations all occupying the same physical volume. The resulting scatter plot produces a clear visualization of the relative behavior of different designs. (This technique was used previously in studies of multi-element spherical antennas [2]). For this study, the overall size was held constant (38×60×4 mm) and only the permittivity and thickness of the thin dielectric layer underneath the top surface, and the gap size, were varied. One-, two-, three-, and five-period designs were considered. For a three-period resonator, a 1.5 mm gap size, and a 0.64 mm dielectric layer of permittivity 10.2, the resonant frequency is 2360 MHz. Gradually reducing the gap to 0.5 mm lowers the resonance to 1828 MHz. Increasing the permittivity to 15 enables the same resonator to vary over a 1577–2287 MHz range for gap values between 0.5-1.5 mm; a permittivity of 17 and a gap size of 0.5 mm has a resonance at 1499 MHz. Similar variations are done for the other resonators, where the parameters were chosen to obtain a sampling of results covering a similar frequency range. (The one-period resonator, for example, required permittivities from 10.2 down to 1 and gap sizes from 2–11 mm to cover a similar range; the five-period resonator required larger permittivities and a 0.128 mm thick substrate to hit the low end of the target frequency range).

The resonant frequency and Q of the fundamental mode of each resonator (i.e., the low frequency, low-Q mode) were computed using numerical eigenmode analysis. Fig. 4 plots the Q versus frequency for all of the simulation results. The Q versus frequency curve for the fundamental mode of a simple patch antenna of the identical size and shape is shown for comparison. The reference patch consists of a 38×60 mm rectangular conducting sheet sitting 4 mm over a ground plane (a 38×50 mm sheet was used for some cases to extend to higher frequencies). For the patch, the entire region directly under the patch is filled with dielectric, and the permittivity is varied in order to vary the resonant frequency. In all cases the resonators sit over an infinite ground plane and the conductors and dielectrics are assumed tobe lossless.

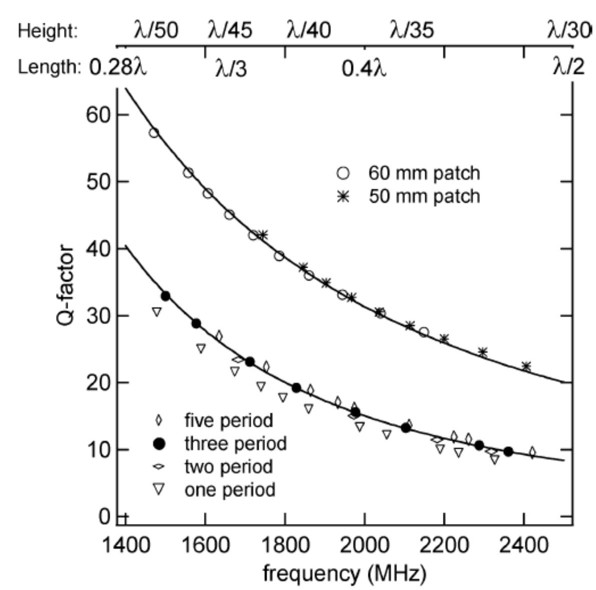

Fig. 4. The radiation Q-factor of the fundamental mode versus resonant frequency for a range of resonator designs of identical size and shape. The corresponding results for a simple patch occupying the same volume are shown for comparison (the dielectric constant of the substrate is varied to change the resonant frequency). The normalized length and height at various frequencies is included at the top of the plot. The solid lines are shown to illustrate trends.

The results in Fig. 4 yield several insights. The Q-factors for the periodic surface resonators all fall close to the same line. Increasing or decreasing the number of gaps does not significantly change the performance with one exception: the one-period resonator has a slightly lower Q than the multi-period structures. The Q of all of the periodic structures, however, is notably lower than the Q of the patch antenna. Over much of the plotted frequency range, there is roughly a 2 × improvement in Q for the periodic surface resonator as compared to the patch. Some insight into this behavior is gained by comparing the radiation pattern of the periodic surface mode to that of the patch. Fig. 5(a) illustrates the far-field radiation in the z-x plane (plane of polarization) for the one- and three-period structures and for the patch structure. Near 2 GHz, the directivity of the patch is 9.1 dBi, whereas the directivity of the fundamental mode of the three-period resonator is 5.4 dBi. The one-period resonator is similar to the three-period, though it radiates a slightly higher power level towards the horizon as compared to zenith (which explains its slightly lower Q as compared to the three-period structure). These results suggest an inherent tradeoff between directivity and Q-factor, and this is confirmed by plotting the ratio of directivity to Q (D/Q) for a subset of the simulation results, shown in Fig. 5(b). By this measure, the patch and the periodic surface resonators behave comparably (for the case of an infinite ground plane).

The variation in directivity between the periodic resonator and the patch is easily understood by considering the periodic resonator structure as an array of radiating slots. For the fundamental mode of the periodic surface resonator, each slot radiates with equal magnitude and phase. To illustrate the effects of this, we consider the two-period resonator. In the structure considered in the eigenmode study in Fig. 4, the two gaps are located 15 mm to either side of the center, but the location of these two gaps can be varied. The effects of varying the gap position on the resonant frequency, Q, and directivity are shown in Fig. 6. As the gaps are moved towards the outer edges of the structure, the path difference between the fields radiating from the two slots towards the horizon approaches a half-wavelength, whereas the radiated fields are always in phase at zenith.

Therefore, the horizon radiation is subject to destructive interference and the directivity at zenith increases as the gaps are moved apart, and the likewise Q increases. In the limit where the gaps are a the outer edge of the structure, the two-period surface resonator looks like a patch antenna. The D/Q results for the various gap positions are also plotted in Fig. 5(b), and follow the same trend line as the other structures.

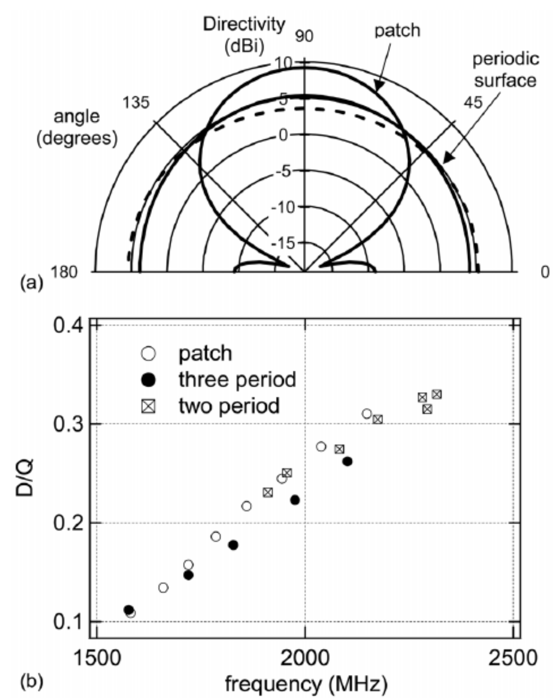

Fig. 5. (a) The far-field radiation pattern of the fundamental modes of the periodic surface resonator (the solid line is the three period resonator at 1976 MHz, the dashed line is the one-period resonator at 2327 MHz) and the patch (60 mm length patch at 2148 MHz). These are simulated E-plane patterns on an infinite ground plane. (b) The ratio of directivity to Q for a subset of the results from Fig. 4 and for the two-period gap position variation results from Fig. 6.

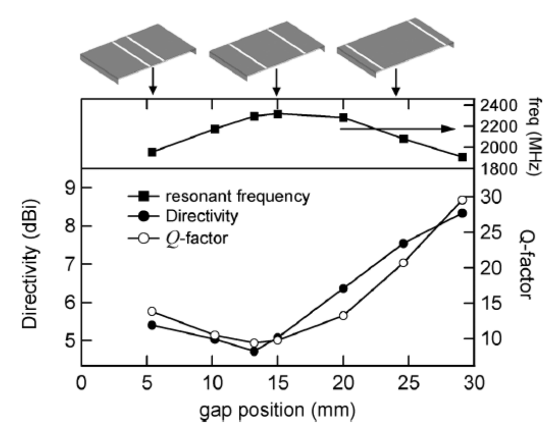

Fig. 6. The resonant frequency, Q-factor, and directivity for the two-period resonator when the position of the two gaps about the center is varied. The gap position represents the distance from each gap to the center of the surface. For this resonator, the gap size is 1 mm, and the substrate has a thickness of 0.64 mm and a permittivity of 3 (the substrate sits just under the top surface and the total thickness of the resonator is 4 mm). The ratio of D/Q for these results was shown in Fig. 5.

III. ANTENNA DESIGN AND MEASUREMENTS

In order to form an antenna from the resonator, a feed must be introduced. The feed structure is located underneath the periodic surface as illustrated in Fig. 7(a) (a three-period resonator is used to form the antenna). The antenna is fed through the underlying ground plane by a short pin that is connected to a 1.5 mm wide conducting strip running parallel to the ground plane. This strip is left open-circuited at the end point opposite the feed. The feed current in the conducting strip electromagnetically couples to the resonant modes of the resonator (in a manner similar to that seen in an L-probe fed patch antenna [3]). The antenna is impedance matched to 50 ohms by choosing the appropriate length, position above the ground plane, and permittivity of the material under the strip. For the antenna presented here, a shunt capacitor at the feed point was also used to assist in the matching. We note that at the operating frequency of this antenna, its thickness is .

The antenna is assembled from two separate printed circuit board (PCBs), with a side view of the structure shown in Fig. 7(b). The top conducting layer (with the three gaps) is fabricated on a 0.64 mm thick layer of RO3010 ( ) and the feed strip is fabricated on a 1.524 mm thick layer of RO4003 ( ). The top PCB sits on two metallic pieces located at each end of its length; these serve both to suspend the top PCB at a specified height (such that the top is 4 mm above the ground) and to provide a conductive connection between the ends of the top conductor and the ground plane. The electrical connection between the top layer and the supporting pieces is achieved using an array of vias along the edges of the PCB and a continuous narrow conductive layer along the bottom of the PCB at the ends. The top PCB is screwed down onto the supporting pieces at three points on each edge, insuring a good electrical connection. The feed PCB is attached directly to the ground plane and fed by a short pin through an SMA connector on the underside of the structure.

The return loss versus frequency for the measured antenna is shown in Fig. 8. For this antenna, the gaps are 0.75 mm, the feed strip is 25.5 mm long (centered within the structure), and 1.7 pF of capacitance is shunted across the feed to ground. The antenna achieves a 10 dB return loss bandwidth of 12.4%. At the center of the band, the of the fundamental mode of this antenna is expected to be ; the presence of a higher order resonant mode broadens the impedance bandwidth by over that expected for a single resonance antenna with this [2]. The higher order mode results from the interaction of the feed line with the fundamental mode of the resonator, in a manner similar to that seen in a patch antenna fed with an L-shaped probe [3]. An L-probe is effective in broadening patch antenna bandwidth when the thickness of the patch is [3]. For the periodic surface antenna (PSA), the L-probe is effective at broadening the bandwidth at a much smaller thickness of (this does not occur in L-probe fed patch antennas of this thickness). There are other higher-order resonant modes in the three-

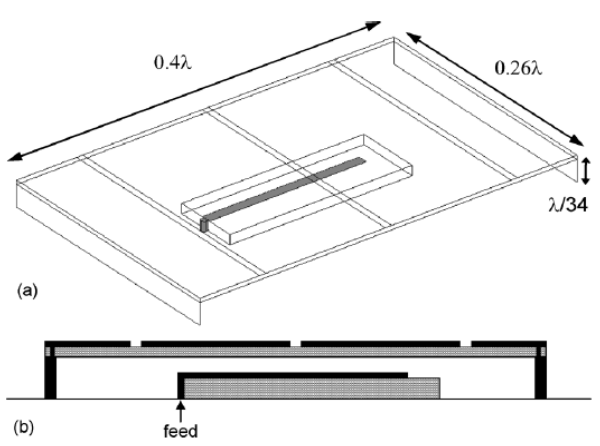

Fig. 7. (a) The three period antenna, and its normalized dimensions at the operating frequency. (b) Side view of the antenna structure. The antenna is constructed from two separate printed circuit boards, and is fed through the ground plane.

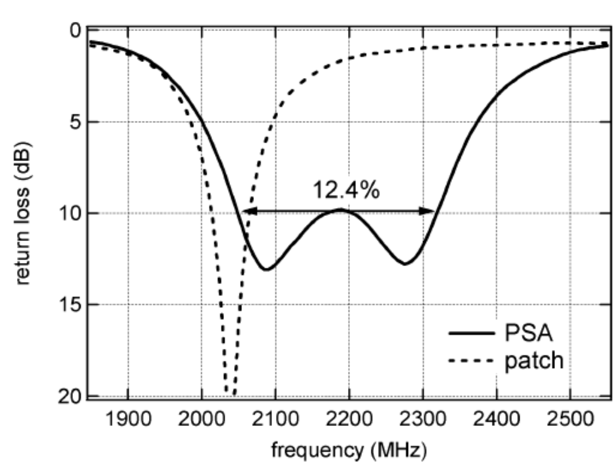

Fig. 8. Measured return loss versus frequency for the three-period antenna and the patch antenna of identical size.

period resonator [including the modified cavity mode similar to that shown in Fig. 2(b)], but these occur at higher frequencies and do not contribute to the bandwidth broadening. We have also designed a one-period PSA of the same size and operating frequency, and observe a similar multi-resonant impedance (with a slightly wider bandwidth due to the lower -factor of the fundamental mode in the one-period resonator).

The measured performance of a conventional patch antenna occupying the same volume is shown in Fig. 8 for comparison. The patchwas fabricated using a 0.64mmthick layer ofRO3010 ( ) which is suspended by non-conducting posts such that the thickness of the patch is 4 mm, with most of that thickness being composed of air. It is fed with a pin through the underlying ground plane. The patch antenna exhibits single resonance behavior with a 10 dB return loss bandwidth of 2.4%. The 5.1 bandwidth improvement factor of the PSA is derived from a patch operating at the low edge of the PSA bandwidth. A patch operating at the center of the band would have a wider bandwidth; this comparison would yield an improvement factor closer to ~4.5×.

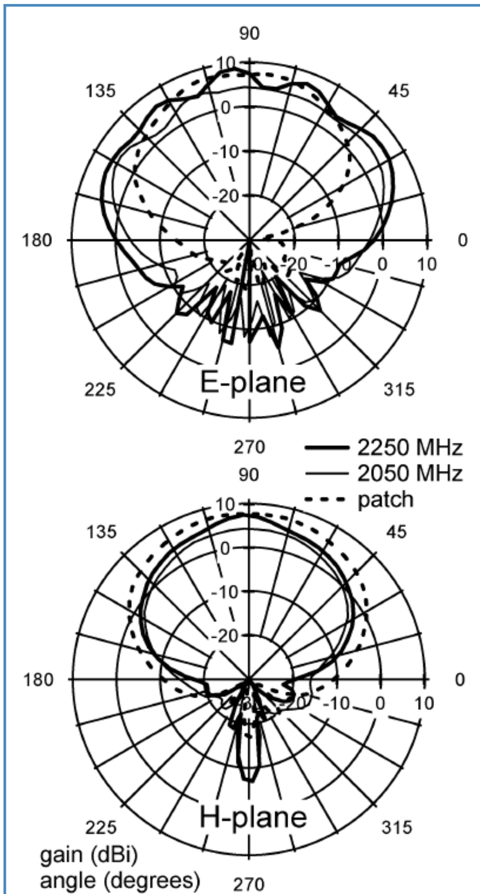

Fig. 9. Measured far-field radiation patterns for the three-period antenna (at two frequencies) and the patch (at 2030 MHz). The antennas were mounted on a 2 foot diameter circular ground plane.

The radiation patterns of the PSA and patch antenna are shown in Fig. 9. The measurements were performed with the antennas mounted on a two foot diameter circular ground plane. The most notable difference in the patterns is seen within the -plane, where the PSA has relatively strong radiation at the horizon, as expected from the simulated patterns of the fundamental resonant mode on an infinite ground plane, shown in Fig. 5 (where the power at the horizon in the -plane is within a few dB of the value at zenith). The strong power at the horizon is not due to surface waves (perfectly conducting surfaces are assumed in the simulations) but is simply a characteristic of the fundamental radiation mode, which resembles a horizontal magnetic dipole. In the measured structure, which has a finite ground, some of this energy diffracts off the edges of the ground plane, producing ripple in the far-field pattern at 2250 MHz, and yielding peak gain values at this frequency roughly equal to that of the patch antenna ( ). The ripple effect is not as pronounced at 2050 MHz, where a peak gain of is observed, closer to the value predicted by simulations on an infinite ground. The patch antenna has a much smaller radiation component along the horizon, and likewise does not exhibit the far-field ripple.

IV. DISCUSSION

The periodic surface structure studied here offers improved bandwidth compared with a patch antenna of the same size. This improvement results from two components: the lower Q of the PSA, and the multi-resonant impedance response. Though it is possible to improve the patch bandwidth by making it multi-resonant (using either a higher order tuning circuit or a more complex design), this would only make up for roughly half of the observed improvement. This is because the Q of the fundamental mode of the patch is 2× larger than that of the PSA. The reduction in Q comes at the expense of a reduction in the directivity of the antenna, a tradeoff likely to be acceptable for applications where an optimized impedance bandwidth from a low profile radiator is desired.

The one-period PSA is similar to the "flush strip inductor" antenna described by Wheeler [4]. In Wheeler's version, the top surface is flush with the surrounding ground plane and the depth of the resonator is sunk into a cavity below the surface. Wheeler briefly mentions the feed, which is described as "another (smaller) resonator located within the cavity," and which yields a double resonant impedance response. (Another version of the one-period structure was recently studied by Erentok et al. [5], though in a different aspect ratio and electrical volume than considered here.) The primary advantage to the multi-period antenna over the one-period antenna is its improved broadside gain relative to the horizon gain [see Fig. 5(a)], and the ability to explicitly trade off directivity and bandwidth over a range of values in the two-period version.

The resonant modes of the one-dimensional periodic surface resonators are similar to the resonant modes found in other types of more complex periodic structures that have been studied to improve the bandwidth performance of low-profile, broadside radiating antennas [6]–[10]. When used solely for the purpose of improving the bandwidth characteristics of thin resonant antennas, these surfaces can be viewed simply as radiating resonators, with a characteristic resonant frequency and Q-factor. Antennas using complex periodic structures as substrates are ultimately limited by the same D/Q limitations versus electrical size that we have observed in the PSA. For linearly polarized antennas, there is not a compelling reason to use two-dimensional periodicity; one-dimension suffices to generate the appropriate resonant mode. The results presented here suggest that complex designs do not yield improved bandwidth over simpler designs for miniaturization and height reduction.

V. ACKNOWLEDGEMENTS

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