A microstrip patch antenna using novel photonic band-gap structures.

by Yongxi Qian, Roberto Coccioli, Dan Sievenpiper, Vesna Radisic, Eli Yablonovitch and Tatsuo Itoh

Printed antennas exemplified by the microstrip patch antenna offer an attractive solution to compact, conformal and low cost design of modem wireless communications equipment, RF sensors and radar systems. Recent applications have pushed the frequency well into the ram-wave region even in the commercial arena as evidenced by the worldwide race to develop advanced collision warning radar systems for automobiles at the 76 GHz band.[1] Microstrip-based planar antennas fabricated on a substrate with a high dielectric constant (Si, GaAs and InP) are strongly preferred for easy integration with the MMIC RF front-end circuitry. However, it is well known that patch antennas on high dielectric constant substrates are highly inefficient radiators due to surface wave losses and have very narrow frequency bandwidth (approximately one to two percent). This situation becomes extremely severe as applications move to higher frequencies, resulting in patch antennas with reduced gain and efficiency as well as an unacceptably high level of cross polarization and mutual coupling within an array environment. Therefore, much effort has been made recently to realize high efficiency patch antennas on high permittivity substrates, including using the latest micromachining technology.[2,3]

Impressive progress in the new and emerging area of PBG engineering in recent years has the potential to provide a simple and effective solution to the problems of surface and leaky waves. A PBG crystal is a periodic structure that forbids the propagation of all electromagnetic waves within a particular frequency band - called the band gap - thus permitting additional control of the behavior of electromagnetic waves other than conventional guiding and/or filtering structures. Although original research has been focused in the optical regime,[4,5] PBG structures are readily scaleable and applicable to a wide range of frequencies, including microwaves and mm waves.[6] For example, several types of microstrip-based PBG structures have been developed recently and their wide range of applications demonstrated (via various prototypes), including harmonic tuning for high efficiency power amplifiers, spurious-free band-pass filters and leaky-wave suppression in conductor-backed coplanar waveguides.[7-9] Full-wave electromagnetic characterization of PBG materials has also been studied comprehensively by utilizing both finite-difference time domain (FDTD)[10] and finite element method techniques.[11] Although relatively new to the microwave community, PBG structures are expected to attract increasing attention in the coming years due to their great application potentials, many of which have yet to be demonstrated.

This article proposes a novel 2-D PBG lattice that is designed specifically to enhance the performance of microstrip patch antennas.[12] The unique capability of a properly designed 2-D lattice to forbid the propagation of transverse magnetic (TM) surface waves in a grounded dielectric substrate over a wide frequency range is first described in detail. It is then demonstrated that a substantial improvement in antenna performance can be achieved simply by surrounding a microstrip patch antenna with this 2-D PBG lattice, resulting in a significant increase in both antenna gain and frequency bandwidth.

A PBG LATTICE FOR SURFACE WAVE SUPPRESSION

The dominant surface wave in most practical microstrip patch antennas on a grounded dielectric substrate is the T[M.sub.0] mode, which has no cutoff frequency. Therefore, a 2-D lattice that can prohibit the propagation of the T[M.sub.0] mode along the dielectric substrate was sought. Figure 1 shows a schematic of the proposed 2-D PBG structure, which consists of a square lattice of small metal pads with grounding vias in the center. This structure can be regarded as the planar version of a more general three-dimensional metallodielectric PBG crystal reported recently by two of the authors.[13] Comprehensive fullwave electromagnetic simulations based on the FDTD method in association with proper absorbing and periodic boundary conditions have been performed to analyze the propagation characteristics of this PBG lattice.

Figure 2 shows the dispersion diagram of the 2-D PBG lattice, which consists of square pads with 88 rail edge lengths and 8 mil gaps. The grounding via in the center of each pad has a diameter of 8 mil, and the substrate is 25-rail-thick Duroid with [[Epsilon].sub.r] = 10.2. The three sections in the graph refer to different directions of wave propagation. For each section, the propagation vector [Beta] in the wave vector space is varied along the edges of the irreducible Brillouin zone (BZ) (shaded triangle in the inset). The dotted straight lines represent the propagation in air and in a homogeneous medium with a dielectric constant of 10.2 (equal to that of the substrate). The dash-dot line to the left of the diagram is relative to the T[M.sub.0] mode of the grounded dielectric slab without the PBG lattice. This mode has no cutoff frequency and is responsible for surface wave power losses in most practical patch antennas.

A microstrip patch antenna using novel photonic band-gap structures.

Meanwhile, the three continuous lines represent the lowest order modes of the PBG structure. It can be seen that two complete band gaps exist, which forbid propagation in the 8.60 to 12.66 GHz and 23.44 to 27.36 GHz frequency ranges regardless of the polarization and direction of wave propagation. Figure 3 shows the distribution of electric energy density as well as the electric and magnetic vector fields of the first mode at point X ([[Beta].sub.x] = [Pi]/a, [[Beta].sub.y] = 0, [[Beta].sub.z] = 0) of the BZ.. These quantities are shown for a single unit cell of the periodic structure and on the plane z = 0.44 mm located inside the substrate and parallel to the ground plane. At point X of the BZ, this mode has a frequency of 8.48 GHz and a strong longitudinal component of the electric field located mainly in the gaps between metallic pads while the magnetic field circulates around the vias. Due to the presence of the strong longitudinal electric field component, this mode can be classified as a TM mode. The electric energy density and the electric and magnetic vector fields of the second mode at the same point X are also shown. The frequency of this mode for the chosen value of propagation constant is 19.02 GHz. This mode can be classified as TE because it has a strong longitudinal component of magnetic field and electric field mainly transverse to the direction of propagation. Consequently, the T[M.sub.0] surface wave cannot couple to this mode. In other words, the band gap for the TM surface wave spans the entire frequency range from 8.60 to 27.36 GHz. As a result, surface waves excited in the dielectric substrate by patch antennas, which have predominantly TM polarization, are suppressed, and improvement in both radiation efficiency and beam patterns is expected.

PBG PATCH ANTENNA DESIGN

Once the proper PBG lattice for surface wave suppression has been determined, the PBG antenna design is straightforward. The patch antenna is designed in a conventional fashion by itself and then surrounded properly by the 2-D PBG lattice. Figure 4 shows a Ku-band prototype that was fabricated and tested. A reference patch antenna on a conventional dielectric substrate (without PBG lattice) has also been constructed for comparison. The substrate used is RT/Duroid with [[Epsilon].sub.r] = 10.2 and 25 mil thickness. An inset feed scheme is used here to match the patch antenna to a 50 [Omega] microstrip feedline, although other techniques such as offset feeding at the nonradiating edge, coaxial probe or aperture coupling may also be employed. The patch antenna is designed to work at approximately 14 GHz so that the T[M.sub.0] surface wave it excites into the substrate will be suppressed with the PBG lattice. The patch size is 120 mil x 168 mil. The position of the inset feed for optimal impedance matching is determined using an in-house FDTD code that takes approximately three to five minutes on a Pentium II PC to produce the broadband frequency response of a typical patch antenna. The total width of the dielectric substrate is 800 mil for both the PBG and reference patch antenna, which corresponds to approximately one free-space wavelength at the center frequency. A relatively long (1.4[inches]) microstrip feedline is used to facilitate the E-plane pattern measurement.

ANTENNA MEASUREMENT RESULTS

Figure 5 shows the measured input return loss ([S.sub.11]) of the PBG and reference patch antennas. The reference patch has a minimum return loss of -12 dB at the designed center frequency of 14 GHz and a bandwidth (SWR [less than] 2) of 1.6 percent. Although the return loss level can be improved by further optimization of the inset feed position, the bandwidth remains narrow (approximately one to two percent) on this type of high permittivity substrate.[2] On the other hand, the PBG patch antenna exhibited a measured peak return loss of -24 dB at 14.7 GHz and a bandwidth of 5.4 percent, which is 3.4-times wider than that of the reference patch.

Figure 6 shows the measured and H-plane radiation patterns of the two patch antennas, including both co- and cross-polarization patterns. While the patterns have been normalized for easy visualization, the peak power received by the PBG patch is 1.6 dB higher in the E plane and 1.8 dB higher in the H plane, indicating a clear increase in antenna gain. The slight discrepancy is believed to be caused by the difference in bending the rigid cable for E- and H-plane measurements. The measurement was taken at 14.15 GHz where the two patches have identical input return losses (-9.4 dB).

As can be seen, the PBG patch shows reduced radiation power along the dielectric substrate (90 [degrees] from broadside) and smaller ripples in its E-plane pattern, indicating an effective suppression of the T[M.sub.0] surface wave. The radiation power at the H-plane edges remains the same as that of the reference patch, which is expected since no surface wave is excited and propagates in that direction. The backlobe of the PBG patch is lower than that of the reference because of the same surface wave suppression effect. The slight asymmetry in the E-plane patterns is due to blocking of the SMA connector. It is also important to make sure that cross-polarizations do not degrade significantly with the introduction of the PBG lattice. The measured radiation pattern results show that the cross-polarization levels for the PBG antenna are below -14.7 and -19.1 dB in the E and H planes, respectively (which are only slightly worse than the reference patch).

The gains of the two patch antennas have also been measured using a standard gain-transfer technique. The de-embedded gains of the PBG and reference patch are 6.77 and 5.16 dB, respectively, showing a 1.61 dB gain enhancement with the PBG antenna. This gain improvement is equivalent to a 45 percent increase in the effective radiated power in the antenna broadside assuming that everything else in the entire RF system is the same. Meanwhile, by integrating the radiation patterns to obtain the antenna directivities and comparing them with the measured gains, the radiation efficiencies of the two antennas may be calculated. The calibrated radiation efficiencies of the PBG and reference antennas are determined to be 85 and 83 percent, respectively.

It should be noted that the radiation efficiency measured in this way is the efficiency of total radiation, which should be close for both patch antennas since they are expected to dissipate similar amounts of metal and dielectric losses. However, the surface wave suppression effect as evidenced by the measured radiation patterns is important because it reduces the radiation energy along the substrate and backside of the antenna, which is the major cause of mutual coupling in an array environment.

It should also be noted that although it is possible to realize higher gain using an array of multiple patches, the associated feeding network is not only complicated but also introduces additional feedline losses that tend to reduce the gain. In addition, the array approach does not provide a direct solution to the surface wave problem as mentioned previously. On the other hand, the unique surface wave suppression capability of this new PBG structure might provide a promising solution to the notorious scan blindness problem in antenna array designs.

CONCLUSION

A novel approach for gain and bandwidth enhancement of microstrip patch antennas based on the emerging PBG technology has been demonstrated. The design technique is simple to implement and fully compatible with standard planar fabrication technology. The multifold improvement in antenna performance (wider bandwidth, improved gain, lower backside radiation and beam shape control) makes this new design approach useful for a wide range of applications at microwave and mm-wave frequencies.

ACKNOWLEDGMENT

The authors wish to thank Professor Yahya Rahmat-Samii for kindly providing his antenna range. This work was supported by the US Army Research Office Multidisciplinary University Research Initiative (MURI) under contracts DAAH0496-1-0389 and DAAH04-96-1-0005. This article is an expanded version of a paper originally presented at the 1998 IEEE Radio and Wireless Conference (RAWCON ’98).

References

1. M. Singer, K.M. Strohm, J.F. Luy and E.M. Biebl, "Active SIMMWIC Antenna for Automotive Applications," IEEE MTTS International Microwave Symposium Digest, Denver, CO, June 1997, p. 1265.

2. G.P. Gauthier, A. Courtay and G.M. Rebeiz, "Microstrip Antennas on Synthesized Low Dielectric-constant Substrates," IEEE Transactions on Antennas Propagation, Vol. 45, August 1997, p. 1310.

3. M. Zheng, Q. Chen, P.S. Hall and V.E Fusco, "Broadband Microstrip Patch Antenna on Micromachined Silicon Substrates," Electronics Letters, Vol..34, January 1998, p. 3.

4. E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-state Physics and Electronics," Physical Review Letters, Vol. 58, No. 20, May 1987, p, 2059.

5. J.D. Joannopoulos, R.D. Meade and J.N. Winn, Photonic Crystals, Princeton University Press, 1995.

6. L.J. Jasper and G.T. Tran, "Photonic Band Gap (PBG) Technology for Antennas," SPIE, Vol. 2843, 1996, p. 80.

7. V. Radisic, Y. Qian and T. Itoh, "Broadband Power Amplifier Using Dielectric Photonic Band-gap Structure," IEEE Microwave and Guided Wave Letters, Vol. 8, January 1998, p. 13.

8. V. Radisic, Y. Qian, R. Coccioli and T. Itoh, "Novel 2-D Photonic Band-gap Structure for Microstrip Lines," IEEE Microwave and Guided Wave Letters, Vol. 8, February 1998, p. 69.

9. Y. Qian, F.R. Yang and T. Itoh, "Characteristics of Microstrip Lines on a Uniplanar Compact PBG Ground Plane," presented at the 1998 Asia-Pacific Microwave Conference, Japan, December 1998.

10. F.R. Yang, Y. Qian, R. Coccioli and T. Itoh, "Analysis and Application of PBG Structures for Microwave Circuits," to appear in Electromagnetics, special issue on antenna and circuit applications with photonic band-gap material.

11. L. Zhang, N.G. Alexopoulos, "Finite-element-based Techniques for the Modeling of PBG Materials," to appear in Electromagnetics, special issue on antenna and circuit

A microstrip patch antenna using novel photonic band-gap structures.

applications with photonic band-gap material.

12. Y. Qian, D. Sievenpiper, V. Radisic, E. Yablonovitch and T. Itoh, "A Novel Approach for Gain and Bandwidth Enhancement of Patch Antennas," 1998 IEEE Radio and Wireless Conference (RAWCON '98) Digest, Colorado Springs, CO, August 1998, p. 221.

13. D. Sievenpiper and E. Yablonovitch, "Eliminating Surface Currents with Metallodielectric Photonic Crystals," 1998 IEEE MTT-S International Microwave Symposium Digest, Baltimore, MD, June 1998, p. 663.

Yongxi Qian graduated from Tsinghua University, Beijing, China, in 1987 and received his ME and PhD degrees from the University of Electro-Communications, Tokyo, Japan, in 1990 and 1993, respectively. He worked as an assistant professor at the University of Electro-Communications from 1993 to 1996, and is currently an assistant research engineer at UCLA. His research interests include electromagnetic field analysis and simulation, passive components, RF photonic devices and planar antennas as well as system architectures based on active integrated antennas. He has co-authored one book and two book chapters, and published over 10 technical papers within the area of microwave and millimeter waves. Qian can be reached via e-mail at yqian@ucla.edu.

Roberto Coccioli received his degree, cum laude, in electronic engineering and his PhD from the University of Florence in 1991 and 1995, respectively. In 1995, he was a visiting scholar at McGill University, Montreal, Quebec, Canada, and in 1996 at the University of California, Los Angeles. He is currently a postdoctoral researcher at UCLA where he conducts research on modeling and simulation of photonic band-gap materials for applications at microwave and optical frequencies as well as numerical modeling of nonlinear semiconductor devices. Coccioli is a member of the IEEE.

Dan Sievenpiper received his BS in electrical engineering from the University of California, Los Angeles in 1994. He is currently completing his PhD in electrical engineering, also at UCLA. His thesis work involves a new type of high impedance ground plane for antenna applications. Other research includes 3-D electromagnetic band-gap structures at microwave frequencies, and 2-D vertical cavity arrays for nonlinear optical image processing.

Vesna Radisic received her Dipl Ing in electrical engineering from the University of Belgrade, Yugoslavia in 1991, and her MS degree in electrical engineering from the University of Colorado at Boulder in 1993. From 1994 to 1995, she was with Ortel Corp. where she was involved with broadband RF/fiber-optic transmitters and receivers. She is currently working toward her PhD degree at UCLA. Her research interests include microwave circuit and active antenna design.

Eli Yablonovitch received his PhD degree in applied physics from Harvard University in 1972. He worked for two years at Bell Telephone Laboratories and then became a professor of applied physics at Harvard. He joined Exxon in 1979 to perform research on photovoltaic solar energy. Yablonovitch joined Bell Communications Research in 1984 and served as a distinguished member of staff and director of solid-state physics research. In 1992, he joined the University of California, Los Angeles where he is a professor of electrical engineering and director of the ARO Photonic Band Engineering MURI.

Tatsuo Itoh received his PhD degree in electrical engineering from the University of Illinois, Urbana in 1969. He has worked at the University of Illinois, Stanford Research Institute, University of Kentucky, AEG Telefunken in Germany and the University of Texas at Austin. In January 1991, he joined the University of California, Los Angeles as professor of electrical engineering and holder of the TRW Endowed Chair in Microwave and Millimeter Wave Electronics. He is currently director of the Joint Services Electronics Program (JSEP) and is also director of the MURI program at UCLA.