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Embedded Millimeter Wave Photonic Crystals as Processing Elements in Shipboard Superstructures

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Abstract:

The ability to rapidly and accurately detect signals is essential in the modern warfare environment. However, the ever increasing use of the spectrum places great demand on current technology and, thus, requires significant technological developments to overcome current limitations. In addition, the nearly ubiquitous miniaturization of military systems requires a concomitant reduction in the size of radiating apertures. Therefore, in order to deal with these challenges, we utilize advanced artificial materials, namely, photonic crystals (PhCs) and meta-materials, to construct an advanced signal sensing head with miniaturized antennas. This sensor can directly detect and process signals in terms of their frequency channelization and direction of arrival and does so at essentially the speed of light. In addition, PhC based devices are electromagnetically transparent, which leads to a dramatic reduction of the scattering cross-section. Furthermore, perhaps the most significant advantage of the PhC approach is that its underlying devices are on the wavelength scale, which results in ultra-compact systems. To this end, this report summarizes our work in this regard and, accordingly, presents an experimentally demonstrated hybrid lattice PhC channelizer and its associated Schottky diodes. Based on these devices, we designed a millimeter wave correlator, which is composed of the channelizer, Schottky diode mixers and spiral antennas. We also present our design and simulation results of ultra-compact meta-material based split-ring resonators (SRRs) for the realization of physically small, yet electrically large antennas.

1. Introduction

A critical capability in the modern warfare environment is to rapidly and accurately detect and process electronic warfare signals. However, the spectrum of such signals is increasing very fast, which stresses the limits of current and next generation technology. In addition, there is also a pressing problem with limited space and location for such processors as well as accommodating the numerous radiating apertures that are needed to intercept the signals. For this reason, there are significant efforts underway that aim to construct highly sensitive and compact systems by integrating multiple functions into the superstructure such that the sensor head can directly capture and process signals. This process is difficult to solve using conventional electronic based sensing systems, due to the space and power requirements of the requisite devices and systems.

To address this, new and novel technologies need to be developed. One possible means to accomplish this is to use advanced artificial materials, namely, photonic crystals and meta-materials, to construct the sensing head with miniaturized antennas as the detecting device. This sensor head will be based on the unique dispersion properties of photonic crystals to achieve waveguiding and correlation. The main advantage of this approach over conventional techniques is that these devices are, to a large extent, electromagnetically transparent and therefore have a significantly reduced scattering cross-section. Perhaps more importantly, photonic crystal components permit the realization of RF structures on a scale comparable to the RF wavelength, which enables the design of waveguides and antennas that are small and compact in size.

In addition, to reduce the overall size of the sensor head it is also desirable to reduce the size of the detecting antennas. To address this problem, we used meta-materials, such as split-ring resonators (SRRs) to realize an inductive material that will serve to lower the antenna's resonant frequency, thus leading to a significant reduction in the physical size of the antenna. The main advantage of this approach, over conventional antenna miniaturization techniques, is that the antenna efficiency and bandwidth compromise is kept to a minimum. Also, the small size of the antenna ensures that there is minimum intrusion to the soldier as well as low scattering cross-section if mounted within a structure. In addition, this system can be embedded into composite materials that consist of mainly dielectric materials. Accordingly, this sensor device is capable of immediate processing of large amounts of data with high efficiency. Moreover, this direct data control allows processing of the desired signals without causing interference with other electronic equipment.

Typical resonant antennas, such as monopole and patch antennas are based on a quarter-wavelength or half-wavelength dimensions. Also, a rectangular resonant loop antenna that is omnidirectional in nature has wide appeal in the communication community, but it too has dimensions on the order of a quarter-wavelength on each side. Unfortunately, as these resonant antennas are reduced in size, their wavelength dependency poses a strict limitation in the dimension of the antenna, thus, making it harder to reduce their physical size. In recent years there has been growing interest in the area of novel meta-material devices and their applications. This resurgence of artificial material research is due to

many elements, among which are the innovations in fabrication that provides the ability for the engineering of materials with uniquely desirable properties not readily found in nature for controlling, mitigating and manipulating electromagnetic waves. Thus, in this effort we harnessed the unique properties of meta-materials to increase antenna efficiency and performance, deliver greater bandwidth, and most importantly minimize size and weight that will directly benefit front-end sensing device.

To this end, we designed, fabricated, and demonstrated a compact integrated millimeter wave sensor head that can directly interrogate signals. This sensor head is based on the unique dispersion properties of photonic crystals to achieve confinement, channelization, and correlation. The main advantage of this approach over conventional techniques is that dispersion elements are to a large extent electromagnetically transparent and therefore have significantly reduced scattering cross-sections. In addition, to reduce the radiation aperture we designed SRRs that can lower the antenna's resonant frequency, thus leading to a significant reduction in the physical size of the antenna, while at the same time keeping the antenna efficiency and bandwidth compromise is kept to a minimum. Our first approach is the design, fabrication and characterization of photonic crystal millimeter wave channelizers for the routing and channelizing signals, which is discussed next.

2. Photonic Crystal mmW Channelizers

The underlying physics of this approach is to design PhC channelizers based on the unique dispersion properties of PhCs, which are passive devices that consist of periodic arrays of localized structures, whose material constants, differ from that of the host material. A unique quality of the PhC is its ability to control electromagnetic waves in both their spatial and spectral modes, which allows for wide bandwidth, enhanced capability, small size, low weight and cost warfare signal processing systems. In our previous research, we have demonstrated compact mmW PhC waveguides based on engineering their dispersion properties. By this we mean that these waveguides do not contain any form of lateral confinement by way of physical structures. To this end, lateral control is imposed on the propagating wave by virtue of engineering the band structure of the photonic crystal lattice, which significantly minimizes the cross-scattering section of the structure. In our new approach, we introduce a triangular lattice with point defects in the form of cavities adjacent to the PhC waveguide to form a signal channeling structure, as shown in Fig. 1. In this configuration, signals with a frequency coincident with the resonance frequency of the respective cavity will drop from the waveguide to the cavity, which is the mechanism of channelization. This device is based on a novel design of hybrid rectangular and triangular lattices of air holes on a substrate. In this way, the device is designed both by engineering the dispersion surface of the rectangular lattice and utilizing the bandgap property of the triangular lattice.

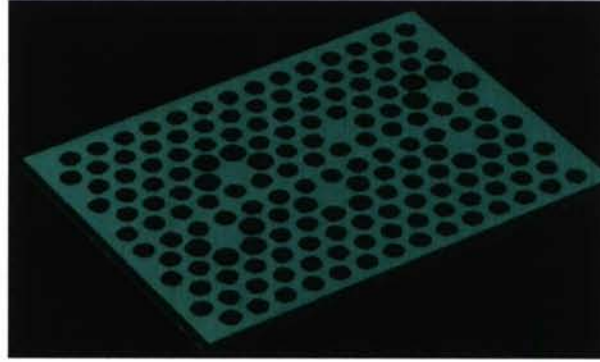


Figure 1. Designed millimeter wave PhC channelizer.

To understand the channeling mechanism of the device, first, we start with the dispersion surfaces, which characterize the relationship between the frequencies, and their associated wave vectors, as shown in Fig. 2. One can obtain dispersion surfaces by solving Maxwell's equations with various computational numerical methods, such as the plane-wave method (PWM), or the finite-difference time-domain (FDTD) method. One way to study the dispersion properties of photonic crystals is to take cross sections at constant frequencies of the dispersion surface to obtain Equi-Frequency Contours (EFCs), as shown in Fig. 2. In this instance, the direction of the group velocity, which is defined as v_g , coincides with the direction perpendicular to the EFC.

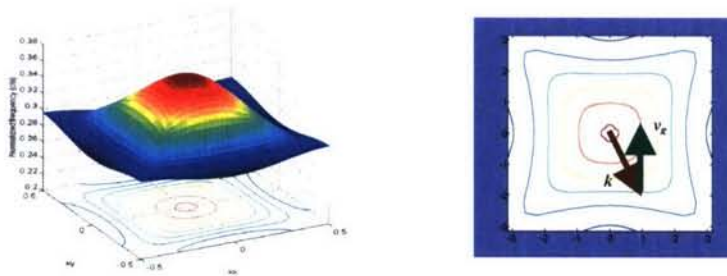


Figure 2. Dispersion surface and EFCs of the PhC.

This gives one the ability to predict the direction of light propagating in a PhC by studying the shape of its EFCs. Unlike ordinary materials which have ellipsoidal-shaped EFCs, PhCs can exhibit a wide variety of EFC shapes, which can be modified by manipulating the parameters of the PhC lattice, such as the lattice type, pitch and fill-factor. If the EFC is a square-like shape, shown as in Fig. 2, the directions of the group velocity are mostly limited to the two directions perpendicular to the square edges. If light is launched toward one edge of the EFC in a wide range of angles, it is only able to propagate in a narrow range of angles in the material. In this situation, light propagation in the PhC is self-collimated. If EFCs were a perfect square, light would propagate in the photonic crystal without any divergence. However, EFCs have curved edges in real structures. As a result, the beam always diverges to some extent as it propagates within

the lattice. To deal with this problem, we created a hybrid lattice structure with a triangular lattice as the boundary to confine the light propagates in the rectangular lattice area. In this configuration, if the wavelength of light is in the bandgap of the triangular lattice, the divergent light, resulting from the curved edges of the EFCs, is reflected back to the waveguide. Therefore, the wave propagating in the rectangular lattice is highly guided without divergence.

By introducing point defects into the triangular lattice, we can realize a channel-drop capability for channelizer applications. Similar structures based on single lattice configurations have been demonstrated to reduce the device size by a factor of hundreds and thousands in the realization of subwavelength lasers. However, to date the high loss of such defect-based devices, as used in this configuration, precludes their use in practical applications. Accordingly, we propose an alternative hybrid lattice channelizer with a low-loss semi-self-collimated waveguide as the channel waveguide to deal with this problem. In addition, the hybrid lattice structure makes it possible to integrate with other PhC devices on a single substrate. The dropping characteristics are controlled by manipulating both the dispersion properties of the rectangular lattice and the parameters of the cavities. Therefore, this configuration is more favorable than general line-defect based channelizers, in which the dropping characteristics can only be controlled by manipulating the parameters of the triangular lattice.

To experimentally validate the design, the hybrid lattice PhC channelizer was fabricated on a 2.38 mm thick dielectric slab with a permittivity of 12.5 using a computer numerical controlled (CNC) machine, as shown in Fig. 3.

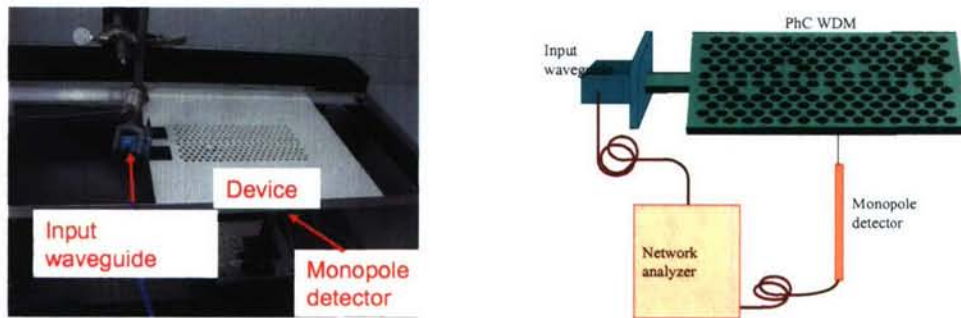


Figure 3. The experimental characterization of fabricated PhC channelizer.

To simplify the structure for initial testing, the fabricated device only consisted of one drop channel. The fabricated structure was characterized using an Agilent 85106D network analyzer based system, shown in Fig. 3. A TE-polarized mmW with the wavelength swept from 10 GHz to 14 GHz was fed into the device. A monopole detector was used to map the surface of the device to detect the surface scattered field. The detected signals were feedback to the network analyzer and processed for the resulting field profiles of the surface scattered fields in the device. To verify the performance of the device, the measured results were compared with 2D-FDTD simulation results (using an effective index to account for the third dimension), which are consistent with one another, as shown in Fig. 4. In both cases, the results show that with the 10.8 GHz wave

entering, the wave drops to the cavity, whereas, with the 12 GHz wave entering, the wave propagates along the waveguide.

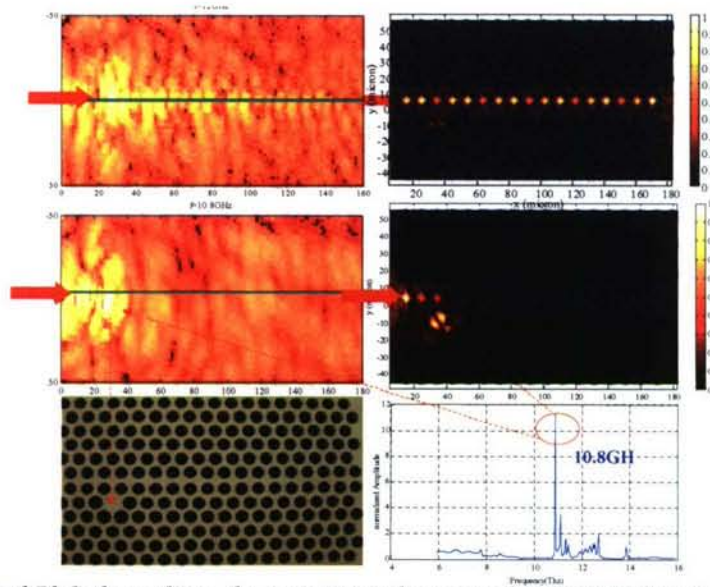


Figure 4. Fabricated PhC channelizer, the experimental measured and 2D-FDTD simulated results.

Encouraged by these promising experimental results, we designed a compact 1 to 8 channelizer and simulated the structure using 2D-PWM method, shown in Fig. 5.

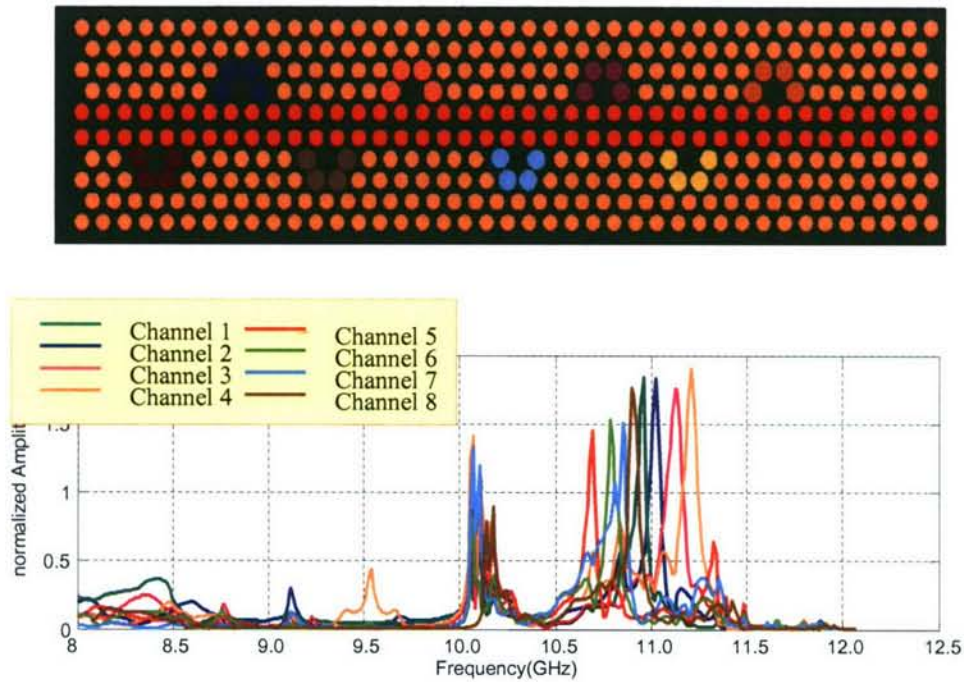


Figure 5. One to eight PhC channelizer and the 2D-PWM simulation results

The 2D-PWM simulation results show that different frequencies drop to different channels. To further validate the design, the channelizer was simulated using 2D-FDTD method, as shown in Fig. 6.

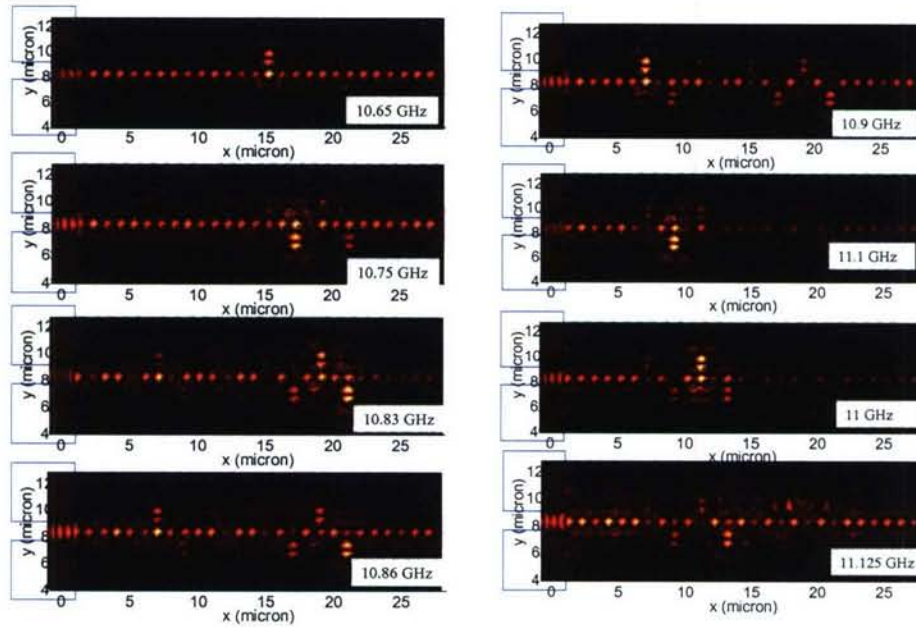


Figure 6. 2D-FDTD simulation results of 8 channel channelizer.

To confirm the simulation results, we fabricated and tested the channelizer using the same methods as described above for single channel device. The characterization results are shown in Fig. 7, which show different frequencies being dropped into different channels.

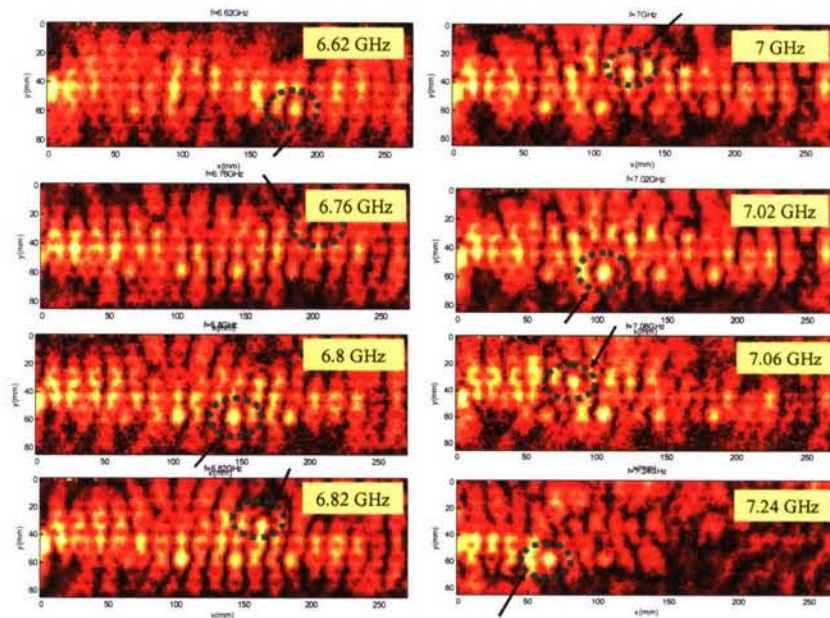


Figure 7. Experimental measured 1 to 8 mmW channelizer.

3. Photonic Crystal mmW Correlator Sensors

As shown in Section 2, both the simulation and experimental results showed the excellent dropping characteristics of the channelizer. As such, this channelizer can be used to design compact correlators, as shown in Fig. 8. In this configuration, two separate signals are captured by spiral antennas which are then fed into a PhC waveguide propagating toward each other. Utilizing the combination of the dispersion and bandgap properties of photonic crystals, we can control the tapping of the counter propagating signals as they interact with each cavity. Since it takes time to propagate down the waveguide, the interaction with the respective cavities corresponds to a time delay between each cavity. As such, the waveguide not only serves as a guiding structure, it also provides the sufficient relative time delay required for correlation of the two signals. Once the two signals are tapped sequentially in time by the cavities a Schottky diode mixer, which is located inside the cavities, serves to multiply the tapped signals with the resulting product being routed through a drop channels and subsequently to a detector, which can be integrated so as to realize the correlation between the two signals.

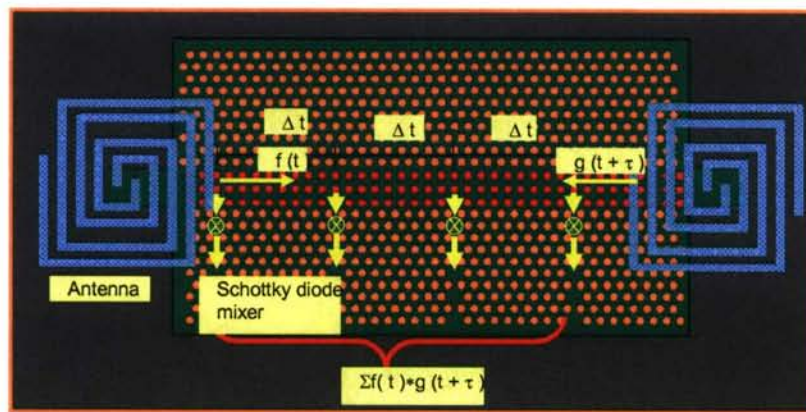


Figure 8. Designed mmW PhC correlator sensor.

To experimentally test the designed correlator, we have designed, fabricated, and tested the Schottky diodes for the multiplication, as shown in Fig. 9.

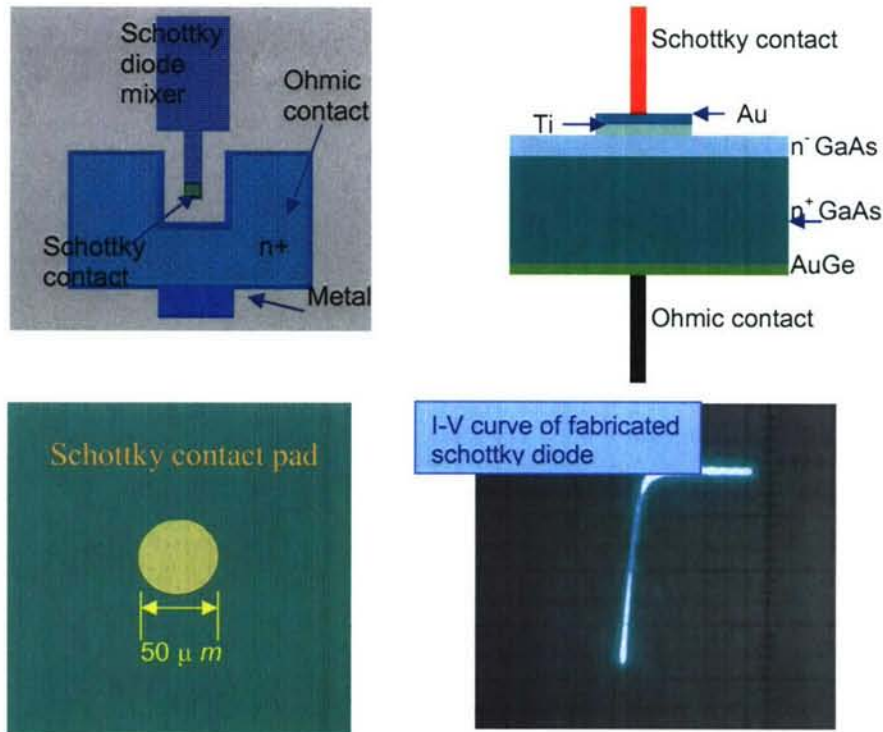


Figure 9. Schematics of Schottky diode and the fabrication and testing results.

4. Ultrasmall Antennas

These results show the possibility of using PhCs to realize a compact correlator as the sensing head. However, in order to eventually decrease the size of the entire integrated system, a reduction in the size of the antennas is essential. To this end, it is possible to physically reduce the size of an antenna by introducing reactive and inductive elements between the antenna and the ground plane. In this aspect of the effort, we designed miniaturized antennas in the microwave portion of the electromagnetic spectrum using synthetic reactive elements in the substrate of the antenna that have the same electrical response as its physically larger counterpart. To realize this antenna, we used metamaterials, such as split-ring resonators (SRRs) to synthesize an inductive material that served to lower the antenna's resonant frequency thus leading to a physical size reduction of the antenna. The main advantage of this approach over conventional antenna miniaturization techniques is that the antenna efficiency and bandwidth compromise is kept to a minimum.

In addition, many other applications make use of physically small, yet electrically large antennas, such as Navy communications. For this reason, the ability to physically reduce the size of the antenna thereby leading to a smaller and lighter-weight communication devices significantly helps to ensure more portability and less interference with other military systems. Therefore, in this aspect of the project we demonstrated prospective loop-antennas for use in communication systems.

Accordingly, a common communication channel is based around the frequency range of 2.4 GHz. Thus, in accordance with such criteria, we designed resonant antennas that are electrically responsive in that frequency range. Typical resonant antennas, such as monopole antennas and patch antennas, are a quarter wavelength or a half-wavelength in dimensions, respectively. Also, rectangular resonant loop antennas that are omnidirectional in nature have a wide appeal in the communication community and typically have dimensions of a quarter-wavelength on each side. However, as these resonant antennas are reduced in size, their wavelength dependence poses a strict limitation in the dimension of the antenna, thus, making it harder to reduce their physical size.

In recent years there has been growing interest in the area of novel meta-materials and their applications in antenna design. This interest in artificial material research is due to many elements, among which are the innovations in fabrication that provides the ability to engineer materials with unique properties for controlling, mitigating and manipulating electromagnetic waves. Thus, in our effort we designed such meta-materials to increase antenna efficiency and performance, deliver greater bandwidth, and most importantly minimize size and weight that will directly benefit electronic device integration on military platforms.

With this in mind, it is possible to physically reduce the size of an antenna by introducing reactive and inductive elements between the antenna and the ground plane. This principle is based on the fact that the resonant frequency of an antenna is inversely proportional to its inductance (L) and capacitance (C), such that an increase in either will decrease the resonant frequency. As a result, in order to increase the resonant frequency back to its original value, the physical dimension of the antenna must be reduced, thus resulting in an antenna with a smaller physical dimension. A caveat to this, based on the above relation between the resonant frequency and the L and C , is that increasing the capacitive element also leads to a reduction in bandwidth, which is undesirable. For this reason, it is more desirable to increase the inductive element, which leads to an increased bandwidth. However, typical inductive elements are based on ferromagnetic materials, and, unfortunately such materials have a very weak electromagnetic response in the GHz frequency range. To overcome this limitation, we propose to use artificial magnetic materials, namely, split-ring resonators (SRRs), which have been shown to exhibit paramagnetic behavior well into the GHz frequency range.

The initial design theoretically demonstrates the ability to reduce the physical size of a loop antenna. To see this, consider a patch antenna sitting on top of a stack of ring resonators, fed by a coax, as shown in Fig.10.

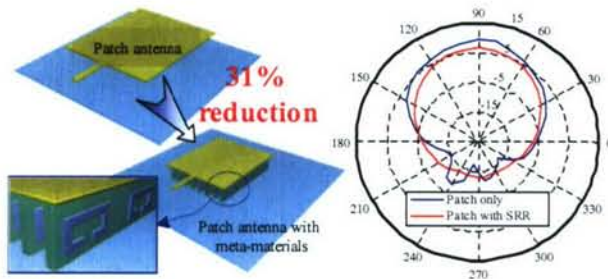


Figure 10. Antenna miniaturization based on the meta-materials. The meta-antenna with 31% reduction in size provides same resonant frequency and similar directivity compared to conventional patch antenna.

and gain of the patch antenna, with and without the SRR slabs, are shown in Fig. 10.

In this effort, we also investigated and engineered meta-materials in term of the shape, dimension, and packaging density of the periodic meta-structures to explore the limitation and maximize the capability of the miniaturization. Additional studies will be carried out for miniaturization in a follow on effort for different broadband and narrowband antennas.

5. Conclusion

In this project, we designed, fabricated and characterized PhCs for millimeter wave signal processing applications. Photonic crystals offer ultrasmall devices because they interact with electromagnetic waves directly on the wavelength scale. In particular, their bandgap and special dispersion properties enable the introduction of defects and engineered dispersion surfaces. In this project, we combined these two properties to design compact mmW one-to-eight channelizer utilizing the combination of these two properties. We also presented our design and initial experimental results of a mmW PhC corrlator and it associated antennas. Most importantly, we can design a compact photonic crystal sensor head, which can directly detect and process signals based on this channelizer. This signal processing method offers ultrawide bandwidth, immunity to electromagnetic interference and flexibility.

To further miniaturize the system, we are consider using a rectangular resonant loop antenna for receiving signals. The rectangular resonant loop antenna is omnidirectional in nature, which also has wide appeal for communications applications. As such, we considered a two-arm spiral antenna that had a broadband and an excellent frequency independent response which, when miniaturized, can have important military applications. However, it has dimensions on the order of a quarter-wavelength on each side. To deal with this, we introduced reactive and inductive elements between the antenna and the ground plane. The simulation results show this structure can achieve 31% reduction in size while provides the same resonant frequency in comparison with conventional patch antenna. In the future, we will continue our work on integrating the

The resonant nature of the SRRs and miniaturization of antennas using such structures has been previously studied. Preliminary studies suggest that the packaging density of the SRRs and the period of the ring stacks underneath the antenna, have a direct correlation with the physical dimensions of the antenna and a size reduction of as much as 25% to 30% can be achieved without compromising the bandwidth of the antenna. A similar radiation pattern

mixers, antennas and the channelizer to obtain a compact mmW sensor head for direct signal processing and communication proposes.

Publication for this program

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4. I. Mirza, S. Shi, Chris Fazi, Joseph N. Mait and D. W. Prather, "A Study of Loop Antenna Miniaturization Using Split Ring Resonators," *IEEE AP-S Conference*, USA. 2007