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Photonic Antenna Reconfiguration: A Status Survey

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ABSTRACT

The primary focus of photonics for antenna systems has, historically, been on the development of link and beam steering techniques. More recent work is focusing on the design of new types of antenna elements or arrays of elements to take advantage of the advances in photonics. By using photonically controlled devices and materials it is possible to produce revolutionary changes in antenna elements and in the design and properties of arrays, opening the door for a new class of antennas — Photonically Controlled Reconfigurable Antennas.

In this paper we survey the history and current status of photonically reconfigurable antennas. This will include the evolution of photonically controlled switches for application in antennas. We look at photonic control of reactive devices and the optically variable capacitor (OVC™) and the evolution of this device towards monolithic integration. Finally, we also will look at the state of photonically reconfigurable silicon and its application to antenna design.

Keywords: antennas, photonics, reconfigurable, OVC, reactive control, photonic switches, photoconductive silicon

1. PHOTONICALLY RECONFIGURABLE ANTENNAS, AN INTRODUCTION

Future communication and radar systems will have strict performance requirements such as bandwidth of an octave or more; frequency diversity; dramatic reduction in size and weight; low observability; and greater isolation from electromagnetic interference. These requirements will necessitate innovative antenna designs. The use of photonic-based antenna feeds, links, and controls opens the possibility of unique, very high performance antenna systems. Historically, the primary application of photonic technology for antenna systems has been on the development of link and beam steering techniques. Over the last few years, however, work has begun to focus on using photonics to produce new approaches to the design of antenna elements themselves. By using photonically controlled devices and materials (switches, reactive devices, photoconductive materials) it is possible to produce revolutionary changes in antenna element and phased array design and properties.

Photonically controlled devices do not require conducting lines running to them in order to provide power or control signals but instead use fiber optical cables or direct optical illumination to control the device or to manifest changes in the materials. Using these devices and materials it is possible to remotely change the effective characteristics (such as gain, tuning, bandwidth, and RCS) of an antenna aperture. Hence, photonics has opened the door for a new class of antennas - Photonically Controlled Reconfigurable Antennas. Reconfigurable antennas hold a great deal of promise because they can combine high gain, conformability, and multi-functionality. Figure 1 schematically illustrates the idea of placing optical control in the arms of the antenna itself.

Some of the potential capabilities that this class of reconfigurable antennas can provide are:

1. Multiple-band antenna systems can be designed by having multiple locations on the antenna structure where load impedances or switches can be controlled in some optimal manner to change the operational band of the antenna.
2. Beam forming and steering can be controlled by adjusting control point impedances or switches on the elements themselves. This eliminates the mechanical steering of a dish or the need for multiple feeds to phased array elements.

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3. Remotely tuning the antenna gives ready access to multiple channels within bands.

4. Remotely tuning or trimming enables the matching network to adaptively respond to the reconfiguration of the antenna.

5. The possibility of low observable (LO) antennas (by controlling the radiation patterns) could have important operational implications.

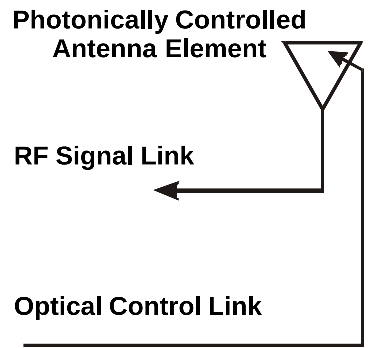

Figure 1 - Schematic of a photonically controlled reconfigurable antenna.

The idea of antenna reconfiguration is not a new one. Antenna designs using diodes or varactors to tune or switch the polarization states of an antenna have been around for some time. Patents by Schaubert[1,2,3] show that placing electronically controlled switching posts in patch antennas allows one to control the frequency, polarization, and directivity of this type of antenna. Similarly, Olesen[4] showed that a quadrifilar helix could be tuned by electrically switching a PIN diode. In these approaches, the antenna elements were strictly controlled by sending electrical signals via metallic wire to control the state of a switching diode.

In a patent by Bhartia[5] a pair of varactor diodes are used to replace the switching diodes as described by Schaubert. This approach allows the impedance of the “post” or “load” to be varied and hence more than two states can be obtained. In particular, the capacitance of the load can be varied by applying a bias voltage via wire. This technique is limited by the need for a bias control signal, which is applied through the feed of the antenna. Electronic reconfiguration using metallic control lines has always been limited in utility because of the interaction of the conducting control lines with the antenna element.

In 1985, Daryoush, Bontzos and Herczfeld[6] introduced the concept of using an optically controlled PIN diode to tune a patch antenna. Figure 2 presents a conceptual presentation of this optically tuned patch antenna. In this configuration, the PIN diode’s impedance characteristics are varied by shining light directly on the device. The light can come via direct illumination or via a fiber optic cable. This approach removes the wire connection and allows the control device to be placed in the plane of the antenna itself since no wire will interfere with the operation of the antenna. In 1988 Daryoush[7] patented this concept.

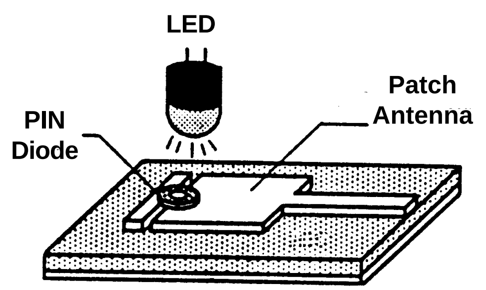

Figure 2 - A Conceptual drawing of the optically tuned patch antenna by Daryoush[6] et al.

In the Daryoush[6, 7] approach shown in Figure 2, a patch antenna is fed by a transmission line. The patch is connected to a short stub by the optically controlled PIN diode. When the PIN diode is reverse biased, only the patch antenna radiates. When the diode is forward biased the radiating area now includes the patch, as well as the short stub. Thus the tuning of the radiating element has changed. Daryoush also showed that if the reactance of the PIN diode is varied by changing the light incident on the device, the radiating frequency could be continuously varied. However, the use of direct optical illumination of a PIN diode has the problem that the quality factor (Q) of the device varies (degrades) as a function of the optical illumination. In other words, the resistance, as well as the capacitance vary and limit the use of this technique as a tuning device. Nevertheless, this appears to be the first use of optically controlled devices to reconfigure an antenna element.

In another 1988 patent, Dempsey[8] presented the concept of the Synaptic antenna. In this concept, a three-dimensional matrix of electrically conductive segments (wires) are configured with “photoresponsive devices” selectively placed between numerous adjacent segments. The “photoresponsive devices” are used as switches to control the path length of the conductive segments. This allows the reconfiguration of the conducting state of the system. Hence, the antenna can be changed by activating or deactivating the “photoresponsive devices.” Figure 3 presents the conceptual drawing, taken from the patent[8], of this system showing two dipoles and feedlines turned on in a three dimensional matrix.

In Dempsey's original patent there is no statement of how these “photoresponsive devices” are to be built. In 1989 Dempsey[9] presented a conference paper on the theory of the Synaptic antenna. In this paper the matrix of thin conductive line segments are joined or synapsed at nodes with photoconducting cells, called Photistors™, which can be turned on by optical energy alone. The Photostor™ was stated to have an equivalent circuit of a 10K ohm "dark' resistor in parallel with a 0.05 pf capacitor which essentially open-circuits the element. When the device is illuminated, the resistor assumes the "on" value of about 1-ohm, effectively shorting the segment. In a companion paper by Bevensee[10] an electromagnetic method-of-moments analysis of a simplified synaptic based reconfigurable array was presented. This analysis showed that the conductive and capacitive properties of the Photistors™ altered the input impedances of the synaptic antenna array structures but did not significantly alter the relative gain patterns. Both Dempsey's patent[8] and original paper[9] are conceptual and theoretical. As far as this author is aware, it was 1996 when the first implementation of the Synaptic antenna was reported[12]. This application is discussed briefly in the next section

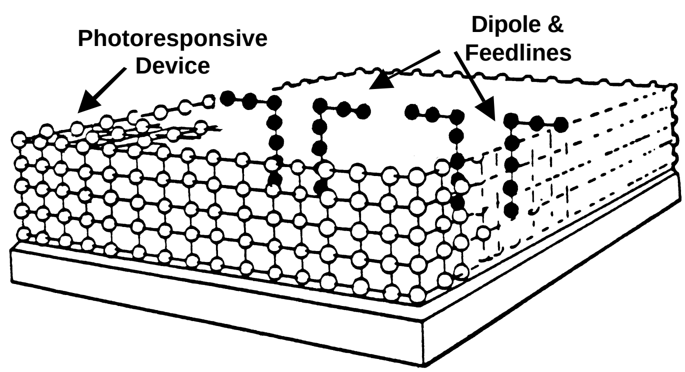

Figure 3 - A conceptual drawing of the generalized synaptic system[9] showing two dipoles and feedlines turned on via photoresponsive devices in a three dimensional matrix.

2. PHOTONIC SWITCHES AND APPLICATIONS

In the previous section we briefly discussed the early history of both electronically and photonically reconfigurable antennas. Photonic switches are the critical technology for most of the photonic reconfigurable antenna concepts. Therefore, several researchers have been developing optically driven switches, which provide the ability to switch between low and high resistive impedances. As proposed in the Synaptic antenna concept, the switch can be used to switch *on* or *off* conductive paths in an antenna or array configuration. Hence, the antenna can be reconfigured to operate in the band or the mode that is desirable. Many of the reconfigurable antenna schemes studied in the past, as well as those presently being investigated, are dependent on switch technology. Here we briefly review the state-of-the-art of photonically or optically driven switches and present some of the most recent applications

Commercially available microwave switches, such as PIN diodes or GaAs MESFETs, are controlled by an electrical bias. In antenna applications, the metal lines controlling the electrical bias can perturb the properties of the antenna element. Clearly, if optical power (delivered by fiber or by direct illumination) can be used to control the switch, then the wires can be eliminated. In addition, minimizing the optical power needed is critical to most antenna applications. Other factors in considering photonic switch design are RF power handling, "off" isolation versus optical power, bandwidth, RF insertion loss, RF linearity, and switching speed. Fortunately, optoelectronic switch technology has been studied for microwave circuits for some time. Microwave optoelectronic switches have several advantages over conventional PIN diodes or GaAs MESFETs besides the removal of a metal wire. Claims have been made that promise faster rise and fall times, broader bandwidth, ability to handle higher power, and simplicity of operation[17].

Two photoconductive materials commonly used to make photonic switches are GaAs and silicon. Both materials exhibit a high dark state DC resistance and a low illuminated state DC resistance. The Photistor™ discussed in the synaptic antenna has been reported to be a silicon photoconductor which can be switched from a 2000 S "off" impedance to a 6 S "on" impedance with 100 :W of light[11] and a useful upper frequency of about 1 GHz. These devices were used by California Microwave, Inc[12] to build a digitally reconfigurable multi-band (100 MHz to 1000 MHz) antenna containing four synapses and twelve optical control fibers, which were used to operate the antenna in three different bands. The high-band and the mid-band synapses were configured as sleeved dipoles. The low band synapses were also sleeved dipoles but they were configured as a two-element array.

In the silicon photoconductor switch, the semiconductor switching material is illuminated directly. Another approach, that has been investigated, is to illuminate a photovoltaic (PV) cell, which then generates a voltage that activates a FET[13, 14] or a PIN[15] switch. These devices are known as PV-FET and PV-PIN switches, respectively. In the PV-FET developed by Albares[14], a 3 S "on" resistance and a >30 MS "off" resistance were reported using optical power less than 1 mW. The PV-PIN switch that was reported was designed to switch a VHF radio monopole antenna length from 90 to 180 cm, thus changing its resonant frequency. The particular application required an antenna that could be operated from 30 to 90 MHz and would handle 25 W of RF power.

The switches discussed so far were used to switch fairly basic dipole and monopole antennas into different lengths. A more complex and innovative, if not ambitious, reconfigurable antenna concept using photonic switch technology is the Structurally Embedded Reconfigurable Antenna Technology (SERAT) which has been reported by Gilbert[16] of Sanders. The basic SERAT concept is comprised of an array of dual-polarized dipole antenna elements whose dimensions can be altered with photonically activated RF switches. These elements are integrated into the top layer of a multilayered composite structure comprised of passive frequency selective surfaces (FSS) that form a broadband ground plane system. The reconfigurable aperture that was reported[16] was a 3X3-array panel that was successfully operated from 500 MHz to 2 GHz. Figure 4 shows a cutaway view of this demo panel.

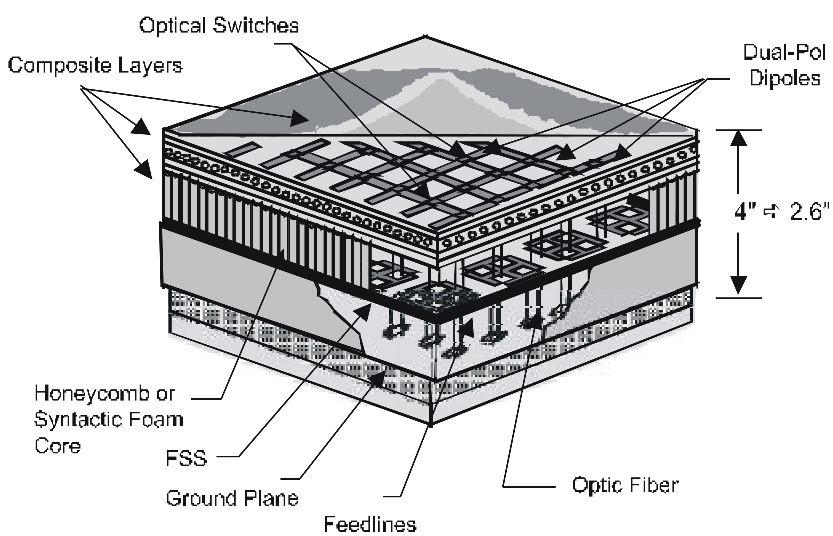

Figure 4 - SERAT[16] demo panel showing arrays of dipoles, FSS, and feeds.

Also in 1996, Charette, et. al.[27] also of Sanders presented a paper discussing the RF and thermal requirements of intrinsic silicon photonic switches used in composite-embedded reconfigurable antennas. The switches studied in their report were used to configure Structurally Integrated Reconfigurable Multi-function Apertures (SIRMAS). The switches were connected in line with the arms of dipole elements to vary the length in order to shift the antenna resonance. This is very similar to the Synaptic antenna of Turk[12] and the switched monopole of Sun[15] discussed above. However, in the SIRMAS system the switches and antenna elements are embedded directly into the composite structure and skin of the host platform. This embedding of the switches has potential thermal implications for the operation of the switch or the composite structure itself. An interesting conclusion from their study was that while an equivalent "on" resistance of 5 ohms is adequate for efficient antenna performance it may be too high for power dissipation in transmit modes because of I^2R problems.
A photonically controlled 3-bit integrated antenna/phase-shifter using the spiral-mode microstrip (SMM) antenna has been developed by Wang[21,22,23] , achieving a 10:1 frequency bandwidth with good performance for array applications. Figure 5 presents a drawing for this SMM antenna. This 7.5”-diameter antenna exhibits good performance over the 0.5 to 5.0 GHz frequency band. The switching method used employs PIN diodes as the RF switches controlled by optoelectronic bias switches. This technique reportedly produces lower insertion loss and higher power-handling capability than that of conventional PIN diode phase shifters.

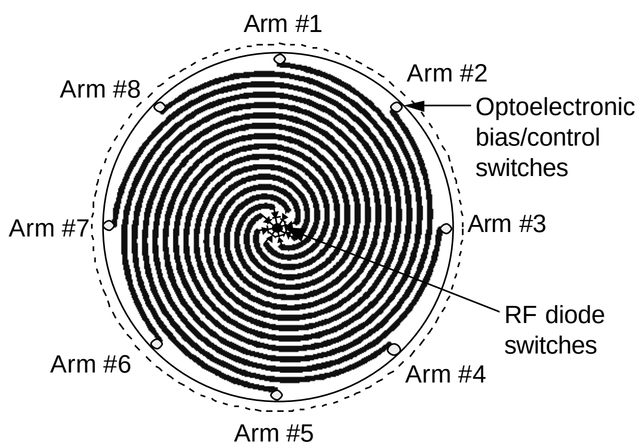

Figure 5 - Design of the Wang [23] 3-bit hybrid SMM antenna/phase-shifter.

3. ANTENNA RECONFIGURATION VIA REACTIVE LOADING

Reactive loads can be used with great effect to control matching, radiation, and scattering characteristics of an antenna. The tuning, gain, or RCS of an antenna or array can be changed by varying the reactive impedance values of control loads placed either in the feed gap or in the arms of an antenna element. Pattern and RCS control is understood heuristically if one considers that the directivity and the RCS of an element are related to the distribution of current over the arms of an element (or over the aperture of the antenna). If this current distribution can be modified in phase and/or magnitude, then the directivity or RCS pattern will be changed.

Tunable antennas have tremendous potential for use in shared aperture or frequency agile antenna arrays. Tunable antennas may be constructed by embedding reactive loads such as varactor diodes within the radiating structure or the feed region. Optical control of varactor diode reactance for reconfigurable antennas offers all of the advantages normally associated with optical links—low-loss, lightweight, immunity to noise, isolation from RF circuit—but has the additional advantage of extremely low optical power requirements as compared with many other reconfigurable antenna technologies.

Varactor diodes may be controlled optically using two techniques: direct control, or indirect control. With direct control, the active region of the device is illuminated with the optical control signal. The same device thus performs both optical and microwave functions, which often involve contradictory design requirements. The maximum achievable capacitance tuning range is also limited for a given range of illumination intensities. Illumination of the varactor diode also leads to a reduction in the Q-factor of the diode. An alternative scheme is indirect control, where the optical control signal is first converted to a suitable electrical form by a dedicated detector. The electrical control signal governs the bias point of the varactor diode, which is part of the microwave network[18].

Two varactor based Optically Variable Capacitor (OVC™) circuits have been developed by Toyon[18] for indirect optical control and are shown schematically in Figure 6. In this approach, the optical control signal is converted to a light dependent voltage by a miniature photovoltaic (PV) array. The photovoltaic array comprises of Schottky or PN-junction diodes connected in series such that the open circuit voltages add up. The voltage developed across the PV-array reverse biases the varactor diode and hence controls the junction capacitance, as shown in Figure 6a. Since the reverse biased varactor draws a small current, the voltage generated by the PV-array is essentially the open circuit voltage. Using this technique it is possible to obtain a larger swing in the voltage (and thereby in varactor capacitance) by simply using more diodes in series in the PV-array. The design is simplified because there are no microwave performance requirements on the PV-array and no optical functions to be performed by the varactor diode.

Figure 6b is a modification whereby the optically induced bias voltage does not appear at the output terminals of the circuit, which would be connected to the RF circuit. This would be especially useful if multiple programmable reactances are required. This OVC™ circuit is made possible by the low drive currents required by the varactors which enables an RF choke resistor to be placed in the bias loop to present a high impedance to the RF circuit. In both cases a very large shunt resistor is required in parallel with the PV array to improve the induced voltage swing under low bias conditions.

In 1995, Toyon[19] reported using the OVC™ for both tuning of electrical small loops and pattern control of spiral antennas. Figure 7 presents a drawing of a hybrid OVC™ placed in an electrically small loop antenna so that the loop can be tuned. Figure 8 shows the tuning obtained for three different size electrically small loops. In this case, the Q was preserved over the entire tuning range of the loop.

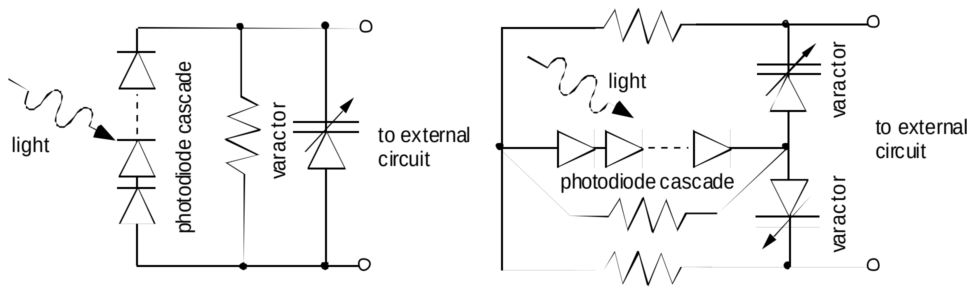

Figure 6 - (a) Basic concept of indirect optical control of varactors. (b) Toyon[18] OVC™ circuit which isolates the optical bias from the RF circuit. In both cases a large shunt resistor is required in parallel with the photovoltaic cascade in order to realize maximum voltage swing

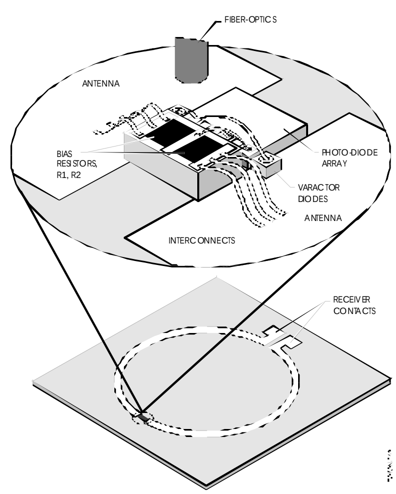

Figure 7 - A schematic of a hybrid OVC™ placed in an electrically small loop antenna.

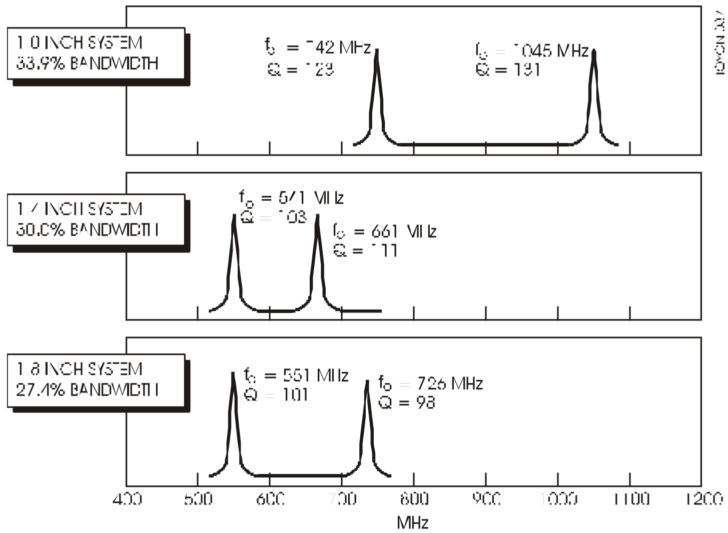

Figure 8 - Measured tuning range for three electrically small loop antennas tuned with Toyon's OVC™.

In 1998 Nagra, et.al.[20] reported a monolithic implementation of the Optically Variable Capacitor circuit in GaAs using a novel lateral oxidation technique for device isolation. A buried oxide isolation scheme was incorporated to prevent substrate leakage that degraded performance of the miniature photovoltaic arrays. The performance of the PV-array and varactor were verified and capacitance versus light curves were generated. A maximum capacitance swing from 1.1 pf to 0.47 pf was recorded. This device has been integrated in planar antenna and other microwave circuit structures. Figure 9 presents the basic setup for a simple optically-tunable planar antenna, and SEM insert showing diodes integrated at the antenna feed.

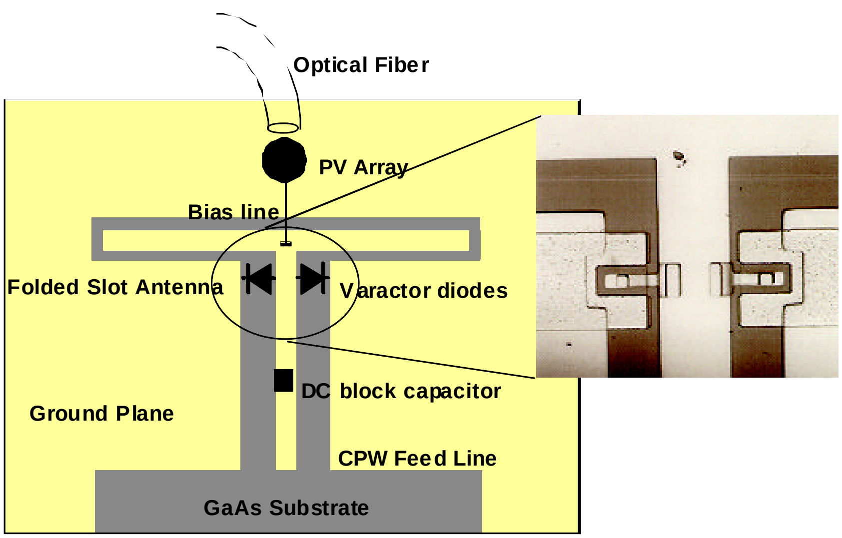

Figure 9 - Basic setup for a simple optically tunable planar antenna, and SEM insert showing diodes integrated at the antenna feed.

4. PHOTOCONDUCTIVE RECONFIGURABLE ANTENNAS

Photoconductive silicon based antennas activated by laser pulses have been investigated vigorously in recent years. A variety of novel technologies have been demonstrated in this area. A semiconductor element will become photoconductive when activated by CW laser illumination, and thus it can serve as a metal-like electromagnetic (EM) radiator[24,25]. When the laser source is off, the antenna element becomes essentially transparent to the EM wave, thus it will give no interference to nearby active elements and also is immune from EM detection. Many of the initial photoconductive reconfigurable antenna studies reported in the literature have used the basic bowtie antenna as the radiating element. Raytheon[24] has illuminated their antenna by shining laser light directly on the element. More recently, Sanders[26] has developed a light tank delivery system that uses optical fiber to feed the light on the element. This system is shown schematically in Figure 10.

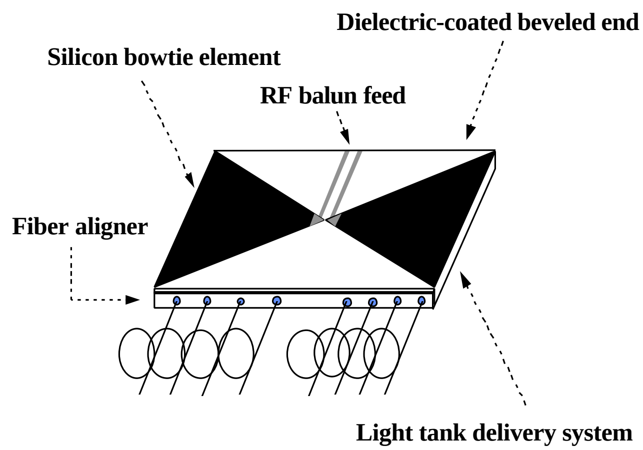

Figure 10 - The schematic of the Sanders[26] light tank delivery system.

Array panels formed by the photoconductive elements as shown in Figure 10 can be stacked in a compact manner, and shared with a common exposure aperture. Sanders[27] has reported developing an antenna array system, named “Structurally-Embedded Photonically Controlled Phased Array Antenna -SEPCPAA” which reportedly provides a broad bandwidth capability, while retaining the advantages of a narrow bandwidth performance. Each panel in the array is designed to radiate a certain bandwidth as a partition of the total broad bandwidth of the system. The sharing of the exposure area or the radome dramatically reduces the system space-extension requirement as well as decreases the undesirable stealth platform’s radar signature.

5. SUMMARY

We have briefly introduced the concept of photonically reconfigurable antennas and have shown examples of different reconfiguration technologies that are most commonly being studied presently. By using photonically controlled devices and materials it is possible to produce revolutionary changes in antenna elements and in the design and properties of arrays. In this paper we surveyed the history and current status of photonically controlled switches for application in antennas. We also looked at photonic control of reactive devices and the optically variable capacitor (OVC™), the evolution of this device towards monolithic integration, and examples of how it is used. Finally, we briefly introduced photonically reconfigurable silicon and its application to antenna and array design.

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