Electronically Controlled Metamorphic Antenna

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Abstract

This paper describes work undertaken since April 2006 to investigate the practicality of an optically addressed metamorphic antenna. The concept is for an antenna or array and its coplanar feed lines, the shape of which can be rapidly changed under electronic control to change its properties. The concept structure includes a photoconducting layer behind which is a pixellated light source. The first objective was to establish the attainable performance of affordable photoconductor layers and compare it with the needs of a tuneable ESM antenna.

Keywords: Photoconducting antennas, Cadmium Sulphide, Thick film deposition

Metamorphic Antenna Concept

This paper describes a novel concept for an antenna or array and its coplanar feed lines, the shape of which can be rapidly changed under electronic control. Such a concept offers the prospect for an antenna whose properties can be dynamically changed, either as driven by requirements or adaptively in response to alterations in environment. It further allows for the possibility of antenna diversity from a single aperture, with switching between modes or roles.

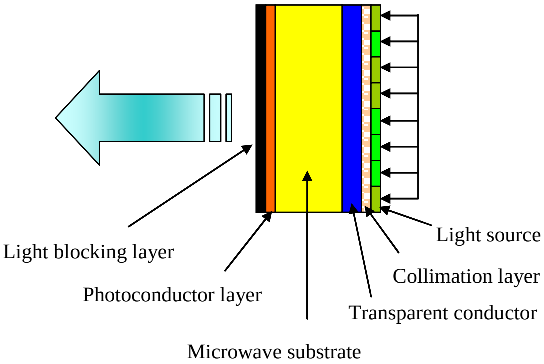

Figure 1 *Metamorphic antenna structure*

The concept is based on the structure shown schematically in Figure 1. It comprises a photoconducting layer behind which is a pixellated light source. Also present are a microwave substrate and a transparent conductor to form a structure similar to that of a printed antenna. The pixellated light source is addressable and reconfigurable, creating changing patterns of high conductivity on the photoconductor. These define antenna elements and associated components. Example antenna changes could include: between two different patch arrays, to alter frequency; changing feed line lengths, to steer a beam; additionally moving elements to give limited adaptability.

The metamorphic antenna concept offers a number of potential benefits to future systems. These include:

- A rapidly and electronically re-configurable, highly versatile antenna technology for electronic surveillance sensors.
- A wide frequency coverage, resulting from a tuneable antenna.
- Electronic beam-steering, giving low susceptibility to grating lobes, and adaptability.
- A compact, thin, low profile, lightweight, possibly conformal, structure. This is especially suited to small airborne platforms (UAVs),

reducing payload restrictions on mass and volume.

- Platform RF signature control through switched frequency or frequency selective surface techniques.

Future ESM systems are likely to place increasing reliance on airborne platforms, exerting challenging demands for compact payloads. In addition greater versatility, a wider frequency coverage and electronic scanning to increase effectiveness are also likely to be required. Hence the metamorphic antenna concept is highly relevant to future ESM systems. In comparison, increased versatility arrays based on current RF technologies may incur weight or cost penalties.

Technical Programme

This paper describes work undertaken since April 2006 to investigate the practicality of an optically addressed metamorphic antenna. The first objective was to establish the attainable performance of affordable photoconductor layers and compare it with the needs of a tuneable ESM antenna. Work concentrated on:

- Development of formulations and processing methods for preparing photoconductive semiconductor layers having the high photoconductivity and high Light to Dark state Conductivity Ratio (LDCR) required for use in a metamorphic antenna.
- Electromagnetic (EM) antenna modelling to define the performance needed from the photoconductor.

The above packages of work were carried out in concert, but are described in separate sections below. For most of the work described, the semiconductor considered for the photoconductor was based on cadmium sulphide (CdS). A review identified this as a good starting point, since it is well established as a photoconductor, and can be processed into large area devices at low cost.

Electromagnetic modelling

Semiconductor properties: Solid state physics theory was first applied to calculate the conductivity and complex permittivity of CdS photoconductive layers as a function of increasing charge carrier concentrations produced by different illumination levels [1-3]. The results were then used in electromagnetic modelling of antennas and associated components.

For the calculations it was assumed that the electron charge carrier density for a photoconductive semiconductor typically varies from 10^{16} to 10^{23} carriers per m^3. As CdS is a n-type semiconductor, only electrons were considered to contribute to the photoconductivity.

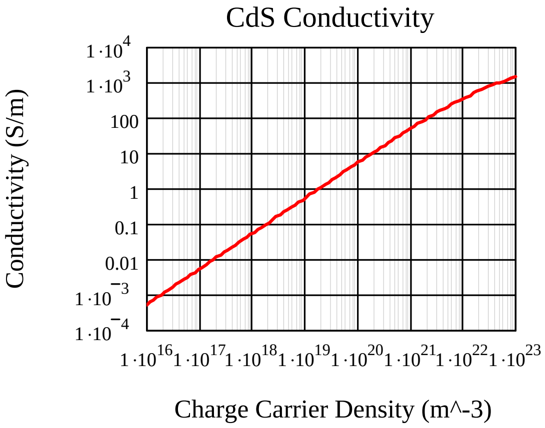

Figure 2 *CdS conductivity vs carrier density*

The predicted variation of RF conductivity with charge carrier density is shown in Figure 2. For low charge carrier densities the conductivity and dielectric loss tangent are low, while the permittivity equals 8.3, that of the lattice. As the charge carrier concentration is increased the conductivity and loss tangent also increase, while the permittivity decreases towards unity. In the range where the permittivity approached unity it was assumed that the photoconductive layer could be considered as a simple metallic material. Consequently, calculated values for conductivity, permittivity and dielectric loss tangent for carrier concentrations up to $5 \times 10^{21} m^{-3}$ (corresponding to a conductivity of 100 S/m) were implemented in the EM modelling of RF structures. Beyond this value it was assumed that the material was a simple metallic material, requiring only a value for conductivity to be used.

Antenna properties: To predict photoconductor requirements for antennas the semiconductor properties calculated above were used in EM modelling to analyse an example microstrip-fed rectangular patch antenna. The active layer was assumed to be formed from a 50 micron thick CdS layer on a 1.1 mm thick glass substrate above a ground plane. The patch antenna was assigned the properties of illuminated photoconductor; the rest of the CdS layer was assumed to be in its dark state. Calculations were performed as a function of photoconductivity and LDCR. Values for permittivity and tan delta were entered according to the carrier concentration derived from the conductivity. As a reference, a metallic patch was also designed above the same glass substrate and ground plane, having the same dimensions as used for the illuminated area of photoconductor.

Predicted antenna boresight gain versus photoconductivity for various LDCRs are shown in Figure 3. The gain was normalised to 6.4 dBi, that of the reference metallic patch. For a given finite LDCR, the gain increases to a maximum as the photoconductivity is increased, but then decreases. The position of the maximum depends on the LDCR value. The decrease occurs because the conductivity of the dark area surrounding the patch becomes sufficient to cause leakage. Below the maximum the dark material acts as a dielectric. For an infinite LDCR the gain simply increases asymptotically to that of the reference antenna.

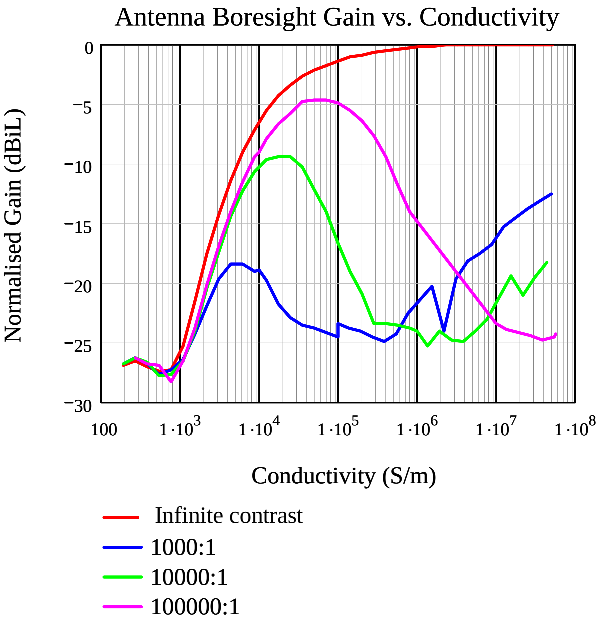

Figure 3 *Patch antenna gain vs conductivity*

A photoconductivity approaching 10^5 S/m and a LDCR of 10^6:1 provide a gain 5 dB lower than that of the reference metallic antenna. These were taken as minimum requirements for antenna applications: a higher LDCR and corresponding conductivity would be advantageous. A similar analysis was undertaken to predict the photoconductor requirements for the transmission lines. It was found that, at minimum, a lower LDCR of 10^4 with a lower photoconductivity of 10^4 S/m are required. It was verified that the predicted skin depth at 10^5 S/m and 10 GHz was ca. 20 microns, thinner than the 50 microns CdS thickness used in this work.

Photoconductor development

Fabrication: Thick film deposition was used to fabricate photoconductor layers, to provide sufficient thickness to exceed the skin depth and give a high optical density. The semiconductor powder was mixed with dopants and a flux, then ground into the liquid carrier, ethylene glycol. The resulting paste was coated onto a substrate and annealed in a tube furnace at a temperature of 250-550C under a controlled atmosphere. For electrical characterisation of the layers, electrodes were deposited on the substrate or onto the semiconductor.

Evaluation: Photoconductivity of the films was measured under illumination provided by a 532 nm laser capable of an output power up to 5 W. The beam was filtered and expanded to provide uniform illumination up to 300 mW/cm^2 at the sample. Although pure CdS does not absorb strongly at this wavelength, doped samples 50 microns thick showed optical densities of ~5. The 532 nm light is representative of the emission from efficient Organic Light Emitting Diode (OLED) light sources being developed by the displays industry.

Effects of composition and doping: CdS is a complex semiconductor. Although it has been explored and used for many years as a photoconductor, aspects of its behaviour remain poorly understood and continue to be the subject of research publications. Some important considerations which affect its performance include:

- The material can form either cubic or hexagonal phase crystals. The latter is more thermodynamically stable.
- There is extensive self compensation of dopants incorporated in the lattice.
- The compound nature of the semiconductor brings an added level of complexity. For example, oxygen incorporated in the system can exist as oxide or sulphate.
- Since layers prepared by the thick film methods are invariably polycrystalline, the photoconductivity can be mediated both by processes within crystallites and at their boundaries and both are implicated in reports in the literature.

Undoped CdS: The starting point was the fabrication of samples based on undoped CdS. Films were prepared using CdS with 5-10% $CdCl_2$ added as a flux to allow annealing of the sulphide at reasonable temperatures. The effect of various dopants on the properties was then investigated.

Copper doping: Copper is widely employed as a photosensitising dopant in the preparation of CdS devices. It introduces gap states which lower the effective bandgap of the material and increase the extinction coefficient at visible wavelengths. Copper doped samples were prepared by mixing copper chloride with CdS in the thick film process.

At copper doping levels of 0.5% and above, the resulting films were highly resistive with a conductivity significantly lower than that of undoped CdS. Samples doped with less than 0.1% copper were photoconductive. The optimum level was 0.05%, where a LDCR of 142 and photo-conductivity of 10^{-4} S/m were obtained.

Oxygen doping: Oxygen improves the photoconductivity of chalcogenide semiconductors. It increases the carrier lifetime through formation of trap states which provide an effective indirect bandgap, or by accumulating at grain boundaries where it forms a photosensitive potential barrier to charge hopping [4,5]. Oxygen acts as a hole trap, with electron carrier mobility remaining high. Dual doping of CdS with copper and oxygen was found to be effective in providing photoconductive films. Annealing in oxygen improved both conductivity and LDCR ratio. It was apparent from the results that the dopants have a strongly super-additive effect on the performance of the film.

Mixed semiconductor host materials: CdS/CdSe hybrid hosts have been described previously for use as photoconductors. CdSe has a higher carrier mobility than CdS, reduces the bandgap and increases the optical extinction. However, it is less receptive to doping with oxygen. A series of tests were carried out to establish the effect of a hybrid sulphide/selenide host on the photoconductivity of the samples, and to establish an optimum composition. A

LDCR of 1.8x10^{6} and a conductivity of 0.6 S/m, were obtained. This LDCR easily met the EM modelling requirement, but a substantial improvement in conductivity was still needed.

Indium doping: Indium as a group III dopant is known to increase the n-type conductivity of chalcogenide semi-conductor systems. As the formulations tested so far had insufficient conductivity for antenna applications, but a considerable margin of LDCR beyond that required, a study was made of the effects of indium doping. Indium presents special difficulties in its use due to the difficulty of incorporating it in the CdS lattice. Four different procedures were tested. The most effective involved evaporating indium onto a CdS film and annealing. Indium could be used to increase the photoconductivity, but beyond a certain point the LDCR was seriously degraded.

Physical and structural characterisation: At this stage a number of physical techniques were deployed to understand the effects which limited the performance of the photoconductor films. Tests were carried out on samples of copper and oxygen doped CdS/CdSe mixtures.

X-ray diffraction was used to probe the crystal habit and homogeneity of the layer. Results were compared with reference data for CdS and CdSe, and demonstrated that the samples had crystallised in the preferred hexagonal form. They also indicated that a successful alloying of the two materials had been achieved.

Hall effect measurements on an indium doped sample indicated a carrier density of 6.7x10^{22} per m^{3} and a mobility of 7.6 cm^{2}/V.s. The latter figure is a factor of about 50 lower than should be available from CdS and a greater factor below that of CdSe. From further work it was concluded that it is the low carrier mobility in the layers which is principally limiting the conductivity of the samples.

Electron microscopy revealed that the morphology of the samples is irregular and that the samples have a low density. (see Figure 4). It was clear from these studies that the CdS layers have a carrier mobility which is too low to provide the conductivity required for antenna applications and that the layer morphology is likely to be a principal contributor to this shortcoming. Studies were initiated into increasing the density of the layers, either by changing the anneal conditions or by secondary Chemical Bath Deposition (CBD) of CdS onto the porous layer. Neither approach was successful. The resulting layers could achieve the required LDCR, but were not able to combine this with a conductivity which approached the target value.

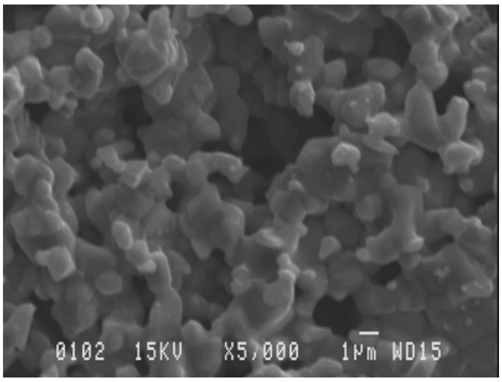

Figure 4 *Electron micrograph of CdS/CdSe layer (x5000)*

Indium sulphide based photoconductors: Indium sulphide was examined as an alternative, less toxic, photoconductor. Processing this material was more difficult than CdS, but good quality films were made using CBD. Optimum samples including silver and oxygen as dopants had conductivity and LDCR approaching those of CdS, but did not improve on it.

Conclusions

The performance available from low cost semiconductor layers has been assessed against the needs of optically addressed metamorphic antennas. It was concluded that:

- Minimum values of 10^4 S/m for photoconductivity and 10^5 for LDCR are proposed for metamorphic antenna applications, but would result in lossy antennas. The requirements could be relaxed for other applications such as short transmission lines.
- Careful control of the processing and doping of CdS yielded a LDCR of up to 10^8 and a photoconductivity up to 60 S/m in separate samples, representing improvements of 10^6 - 10^7 compared to the undoped material. The best formulations overall were based on a CdS/CdSe host doped with oxygen, copper and indium. These achieved a LDCR of 10^4 in combination with a conductivity of ~20 S/m.
- The conductivity in thick film samples of CdS was limited by a porous morphology, yielding low carrier mobility. The same result is expected from other low cost deposition routes. Higher conductivities can be achieved, but at the expense of LDCR. Providing the combination of high conductivity and LDCR needed for an efficient metamorphic antenna under reasonable incident optical power appears very challenging.
- Crystal semiconductors, including CdS and silicon, may be able to achieve a LDCR and conductivity approaching that required for a metamorphic antenna. However the large-area fabrication would be costly and the optical power required would be high (~1W/cm^2).

Recommendations

The realisation of a metamorphic antenna using a low cost photoconductive layer under realistic levels of illumination is extremely difficult to achieve. It is therefore recommended that this approach be halted. However, the requirements on the semiconductor are alleviated in other types of structures, including where semiconductors are configured as switches which link metal elements in a programmable pattern. It is recommended that further work should examine the use of semiconductor switches in segmented antennas and should establish the expected performance of such structures as metamorphic antennas. Adopting a segmented antenna approach will still require high conductivity in the semiconductor. Consequently approaches should follow processing routes which are capable of providing dense, high mobility layers.

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