

# **MILLIMETER WAVE RADIO RESPONDER FOR REMOTE SENSING OF SURFACE CONDUCTIVITY AND LASER LIGHT INTENSITY**

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## **ABSTRACT**

A millimeter wave radio responder was evaluated as a remote sensor of surface conductivity and laser light intensity. A 10 mm CdSe photocell was illuminated by a 1/4 mW, 632.8 nm He-Ne laser light. The photocell was not connected to anywhere. The terminals were left open. The photocell was interrogated by a remotely placed millimeter wave radio responder operated with the frequency of 69.6 GHz and the transmitter power of 3 mW. The millimeter wave radio responder was able to sense the radio echo from the surface of the photocell. The laser illuminated area on the photocell was only 2.86% of the entire active area, yet the radio responder output showed up to 15 dB difference between the laser spot on and off from the target. The minimum reflected signal change observed was 0.002 dB by tilting the target 20 degrees from the normal incidence of the millimeter-wave beam. This was translated to be 0.025% of surface conductance change on the target. This remote sensing was done using an instrumentation of the sensitivity of -40 dBm. Thus, the usefulness and advantage of employing a millimeter wave radio responder for remote sensing of minute change in the surface conductivity and/or the laser light intensity have been demonstrated in this research.

## **INTRODUCTION**

When a target is irradiated by electromagnetic waves, the waves scatter and reflect. The reflected and scattered waves contain information of the target. The irradiator-transmitter send out irradiating electromagnetic waves to the target to be interrogated and a receiver or receivers collect informations of the target by receiving reflected or scattered electromagnetic waves from the target. This is the principle of bistatic radars(1). If the transmitter and the receiver use a common antenna or both antennas are located adjacent to each other with close proximity, it is called the monostatic radar(2). If the target contains a responding transmitter, it is known as the transponder(2). If the target is totally passive, then it is the radio responder(3). The microwave radio responder has been

demonstrated in the past(3). This time, by the use of the microwave radio responder technique operated in millimeter wavelengths, variation of a surface conductivity and laser light intensity illuminating on a surface were remotely sensed and monitored in non-invasive fashion. This millimeter wave radio responder is operated and evaluated this time for non-invasive, non-contact and remote sensing of a surface conductivity and laser light intensity on that laser spot. The millimeter wave radio responder was operated at 69.69 GHz and the interrogating transmitter power of 3 mW. The target was a 10 mm CdSe photocell and a 1/4 mW, 632.8 nm He-Ne laser was used as a light source. The performance of this millimeter wave radio responder as a non-invasive sensor was investigated and evaluated in this paper. This system is basically a monostatic radar when used to tele-monitor the conductivity of the target. But if the conductivity is varied coherently with the laser light and when the system is used to tele-monitor the laser light intensity, it is now the millimeter wave radio responder(3). This approach is useful for various industrial applications involving non-contact remote surface condition sensing. This approach is new due to non-invasive reflection type approaches used as well as the material of the device employed.

## **EXPERIMENTAL SET UP**

A detailed sketch of a CdSe photo-conductive device(4) used as the target of this millimeter wave interrogation is shown in Figure 1. A schematic diagram of an experimental setup of this millimeter wave radio responder is shown in Figure 2.

In Figure 1, the entire area of 78.54 mm<sup>2</sup> of the photo-conductive device was irradiated by millimeter waves and only an area of 4.9 mm<sup>2</sup> was illuminated by the laser light when the device surface was perpendicular to the laser beam as shown in Figure 1. The majority of the device area was covered by metallization and the photo-conductive CdSe was exposed only between the gaps of metallized fingers. The exposed area to the laser light was 2.25 mm<sup>2</sup>. This area was only 2.86% of the entire device area. The energy of the 632.8 nm He-Ne laser light, 1.96 eV was sufficient to excite the excess electrons in the conduction band of this n-type CdSe device. The excitation of the excess electrons was remotely sensed by a non-contact millimeter wave responder. The surface of the device was irradiated by millimeter waves as shown in Figure 2.

As seen in Figure 2, millimeter waves of 69.6 GHz was generated by a reflex klystron VA-250. The millimeter wave output was radiated out from a horn antenna of 15 dB gain through an impedance matching E-H waveguide tuner, a ferrite isolator, an attenuator, a waveguide twist, an E-plane circulator, and another waveguide twist. These two waveguide twists were needed to produce vertical polarization of the electric field vector of interrogating millimeter waves at the horn. The entire area of the 10-mm CdSe photoconductive device was irradiated by the millimeter waves. The millimeter-wave

reflection from the surface of the device was picked up by the same horn antenna and detected through an E-H waveguide turner and a circulator. The relative level of the detected output was displayed on an SWR meter employed as a relative signal level monitor. The relative change in the reflected signals of the millimeter-waves when the laser beam was on and off was recorded for various orientations of the target device. The laser employed was 1/4 mW, 632.8 nm He-Ne laser.

## **EXPERIMENTAL PROCEDURE**

With both the millimeter wave irradiation and He-Ne laser light illumination on the target, the relative reflectron level of millimeter waves from the target was indicated on the SWR meter in Figure 2. When the laser light was turned off the conductivity where there was a spot of the laser light changes. This change in the resistance in a small area of laser spot produces a change in the amount of the millimeter wave reflections. Therefore the SWR meter output display in Figure 2 changes the amount of the display. The difference in the reading of the SWR meter in dB is the ratio of reflected millimeter wave electric fields in dB with the laser light on and the laser light off.

The difference in dB reading of the SWR meter with the laser light on and off were recorded for the cases with various target orientation in respect to the incident laser light direction as seen from Figure 2. The target orientation influences not only the sensitivity of this responder system to the laserlight detecting capability, but also it influences the level of reflected millimeter waves itself. Therefore, with the laser light off, the relative reflected millimeter wave electric field strengths as indicated by the SWR meter output display under various target orientation were also recorded.

## **EXPERIMENTAL RESULTS**

An example of the experimental results is shown in Figure 3. In this figure, the reflection level change is plotted against the orientation angle of the target. The zero degree orientation angle means that the millimeter wave beam is hitting perpendicular to the device surface and the laser beam is 5 degrees from the perpendicular axis to the device surface. For example, at 10 degree orientation of the device, the relative change in the conductivity observed at the observation point can be theoretically calculated. The change at the millimeter wave frequency 69.6 GHz was found to be 3.5%. A corresponding change in the millimeter wave reflected signal level was 0.3 dB, which was the maximum millimeter wave modulation observed at this orientation. This change was easily detected by this -40 dBm sensitivity instrumentation. The minimum reflected signal change observed was 0.002 dB at 22 degree orientation. This was translated to the 0.025% conductance change at the observation point due to the target.

The orientation characteristics of detection sensitivity was calculated theoretically based on the principles of radar cross sections and ray optics. The theoretical equation was found to be

$$E_{rdB} = 40 \log_{10} \frac{(W-\theta L) \cos \theta}{W} \quad [dB]$$

where  $E_{rdB}$  is the relative reflected field strength level in dB and  $\theta$  is the orientational angle which is pictorially defined in Figure 2.  $W$  is the aperture width of the millimeter-wave horn antenna with a square aperture assumption.  $L$  is the distance between the horn antenna aperture and the CdSe device. Theoretical results of this equation are plotted in Figure 4 together with the measured results. In this case,  $W = 1$  cm and  $L = 1$  cm. Comparing the theoretical results with the measured results the theory then explains the observed results well. The orientational characteristics were studied for industrial sensor applications. In some industrial applications, the sensor orientation is not often conditioned by either millimeter-wave, or optical choice. Polarization effects were also investigated. Optical polarization did not produce any effect but the horizontal polarization of millimeter waves, where the electric field vector is parallel to the split cut of the device and the device is positioned at the minimum reflection location, the highest modulation sensitivity was obtained.

## REMARKS ON EXPERIMENTAL RESULTS

In this millimeter wave radio responder, reflected signal power level change  $\Delta P_{rdB}$  is related to the change in voltage reflection coefficient by

$$\begin{aligned} \Delta P_{rdB} &= 10 \log_{10} \frac{P_{r1}}{P_r} = 20 \log_{10} \sqrt{\frac{P_{r1}}{P_r}} \\ &= 20 \log_{10} \frac{\rho_1}{\rho} \equiv \Delta \rho_{dB} \end{aligned} \quad (1)$$

where  $P_{r1}$  is the reflected power with laser off,

$P_r$  is the reflected power with laser on,

$\rho_1$  is the voltage reflection coefficient with laser off,

and  $\rho$  is the voltage reflection coefficient with laser on.

It is well known that the voltage reflection coefficient  $\dot{\rho}$  is related to the normalized load admittance  $\dot{Y}_L$  by

$$\dot{Y}_L = \frac{1 - \dot{\rho}}{1 + \dot{\rho}} \quad (2)$$

Then

$$(\dot{Y}_L + \Delta \dot{Y}_L) = \frac{1 - (\dot{\rho} + \Delta \dot{\rho})}{1 + (\dot{\rho} + \Delta \dot{\rho})} \quad (3)$$

$$\Delta \dot{Y} = \frac{-2 \Delta \dot{\rho}}{(1 + \Delta \dot{\rho} + \dot{\rho})(1 + \dot{\rho})} \quad (4)$$

For small  $\Delta \dot{\rho}$  if the load is pure conductive

$$\Delta \tilde{G} = \frac{-2 \Delta \rho}{(1 + \rho)^2} \quad (5)$$

Therefore, if  $\Delta \rho_{dB} = 0.3$  dB or  $\Delta \rho = 0.07$  from  $\rho = 1$ , then  $\Delta \tilde{G} = 0.035$ . If  $\Delta \rho_{dB} = 0.002$  dB or  $\Delta \rho = 0.0005$  from  $\rho = 1$ , then  $\Delta \tilde{G} = 0.00025$ .

As far as the target orientational characteristics of detection sensitivity of this millimeter wave radio responder is concerned, at the tilt angle  $\theta$ , the linear receiver horn width which intercepts reflected beam is reduced to  $(W - \theta L)$  as seen from Figure 2. Due to the tilting the effective strength of reflected wave will be reduced to  $\cos \theta$ . Therefore, actual effective area of aperture of the receiving horn antenna is proportional to the area of the antenna aperture  $(W - \theta L)$ . Therefore, the received field strength response from the case where  $\theta = 0$ , can be said that  $(W - \theta L)^2 \cos^2 \theta / W^2$ . Therefore

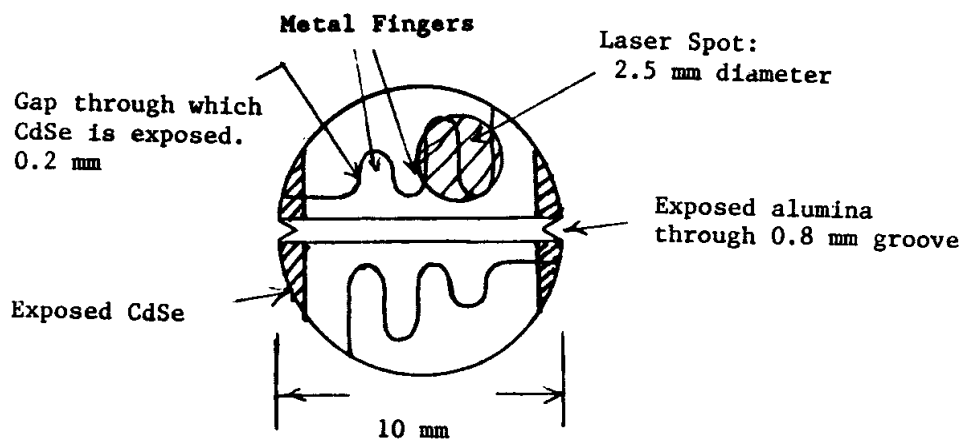
$$\begin{aligned} E_{r dB} &= 20 \log_{10} \frac{(W - \theta L)^2 \cos^2 \theta}{W^2} \\ &= 40 \log_{10} \frac{(W - \theta L) \cos \theta}{W} \end{aligned} \quad (6)$$

## CONCLUSIONS

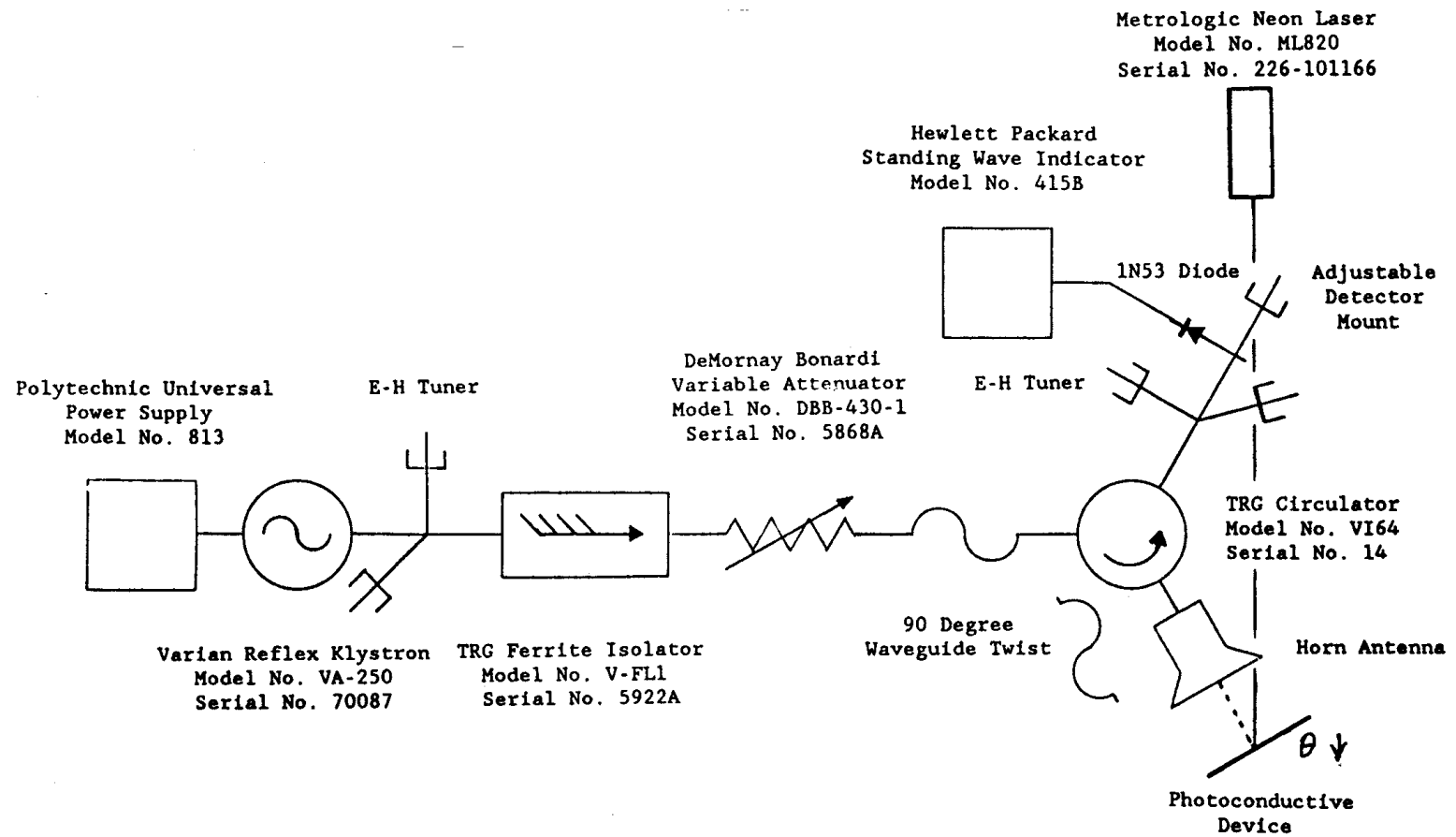
In this research a relationship between the observed reflected power level and the effective target conductivity change were formulated. Responder response for target orientational angle was also formulated. Experimentally, it is demonstrated that this millimeter wave radio responder technique is a useful instrumentation to monitor minute surface conductivity change in non-invasive fashion. It is also found that this technique is useful for monitoring the laser light intensity remotely and wirelessly.

## REFERENCES

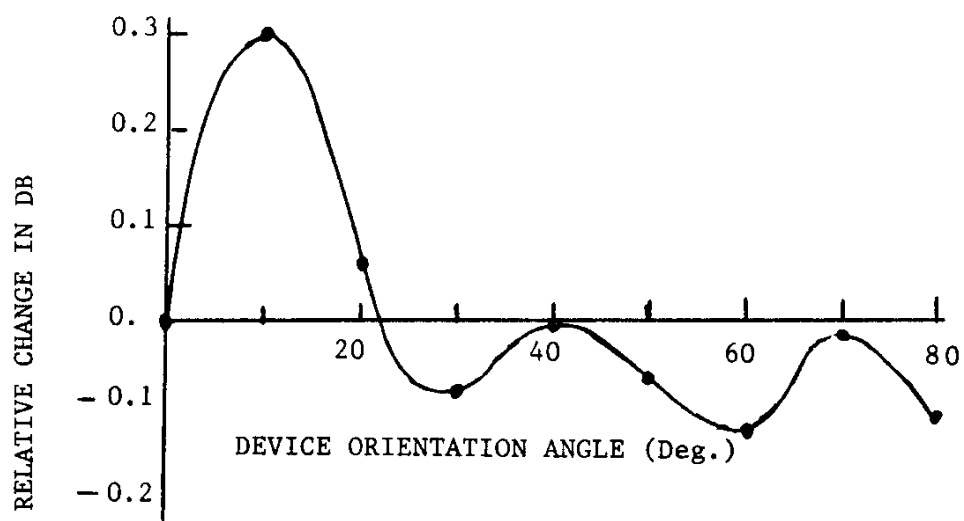
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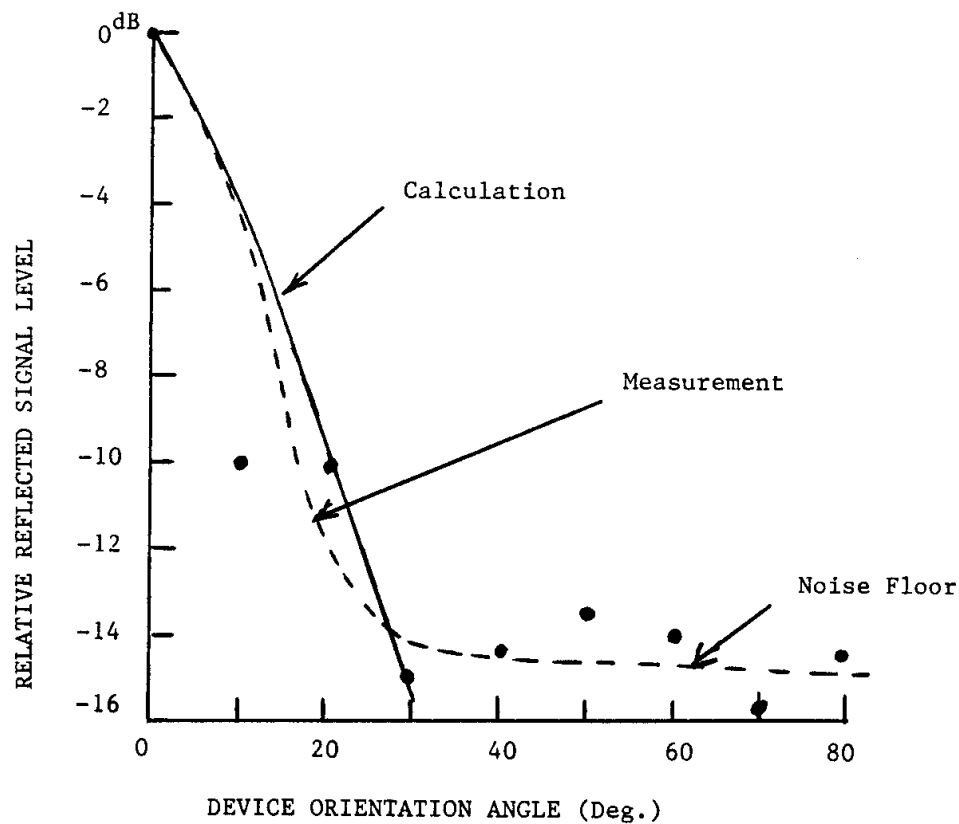
**Fig. 1. Laser Spot Placement on the Photoconductive Device's Front Surface.**



**Fig. 2. Experimental Set-up for the Measurement of the Reflected Power.**



**Fig. 3. Relative reflection level change at millimeter-waves.**



**Fig. 4. Millimeter-wave relative reflected signal voltage level at the responder detector.**