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N-bit Optically Controlled Microwave Signal Attenuator using the Photoconductive Effect

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Abstract

Various optical architectures for N-bit digital control of microwave signals are introduced that use the photoconductive (PC) effect in microwave waveguides for variable rf attenuation control. A 2-bit optically controlled microwave attenuator based on a silicon PC transmission line device is experimentally demonstrated at 990 Mhz. At 532 nm, this attenuator provided 0, 5.8, 11.2, and 15.6 dB of attenuation levels.

Keywords: Photoconductive Switch, N-bit Attenuator, Optical Control, Phased Array Antennas

2. Introduction

Many microwave signal processing systems require variable amplitude control of microwave signals flowing in the system. An excellent example where perhaps thousands of independent amplitude controllers are required is the phased array antenna. In this case, each antenna element is linked to an electronic control box that contains a variable phase shifting device and a separate signal attenuation device. These grey scale attenuator modules perform the necessary system signal calibration and antenna windowing functions.

Today, for most deployed high performance antenna systems, these phase and attenuation control devices are made from electronic switching devices such as PIN diodes embedded in microwave transmission line structures. The variable control is provided by digitally controlled parallel ports to the control modules, with typical values of 6-bit phase control and 8-bit attenuation control with maximum 60 dB attenuation. A typical digitally controlled attenuator module is made up of a current controlled PIN diode attenuator connected to an rf circuit (or transmission line) and a driver circuit consisting of a digital-to-analog converter and a voltage-to-current converter. A typical attenuator module is 4.6 cm by 4.6 cm in area with a height of 2.2 cm, and has an N-bit input port and a power supply port [1]. Thus, it is clear that electronically controlled microwave attenuator modules in a large (>1000) array application require significant electronic control hardware, such as thousands of N-bit digital feed lines, N-bit D-A converters, extended power supplies, and voltage to current converters.

In this paper, we propose the use of optical control of the variable microwave attenuators, thus reducing a significant portion of the antenna panel electronic control hardware. In particular, recently we showed how the PC effect in a coplanar waveguide transmission line fabricated on a silicon substrate can be used for over 30 dB rf attenuation control using a 830 nm pulsed probe/control optical beam [2]. We will show how the PC rf attenuation effect can be utilized to provide the much needed grey scale N-bit digital format optically induced and controlled rf signal attenuation. In addition, this has been performed with the attenuation range optimized for laser power efficient operation, thus minimizing the power hungry localized plasma saturation effects in the silicon substrate. This remote optical control format will provide many benefits to the antenna designer such as smaller electromagnetic interference (EMI) effects, lower unwanted propagation/insertion rf losses, and larger antenna panel open areas for radiator layout and other array functions.

3. Motivation for Optical Control of Microwave Attenuation

The traditional means for controlling the amplitude of individual phased array antenna elements is through the use of electronically-controlled rf and/or microwave attenuators. For a complete description of the state of the art, see for example reference [1]. Our system differs in several very important ways. Phased array antennas typically employ advanced solid-state circuits, with the most typical being referred to as monolithic microwave integrated circuits (MMICs). The common feature of all of these MMICs is that they contain high-speed transmission structures that facilitate the transmission of microwave signals, either from the transmitter to the radiating element, or from the

radiating element to the receiver. In the envisioned case for future phased array antennas, the actual radiating element would reside directly on a MMIC transmit and receive (T/R) module chip. Thus the transmitter, receiver, and radiator functions are all monolithically integrated on a single integrated circuit. In either case, high-speed (i.e., microwave, rf, etc.) signals are routed within each chip by high-speed transmission lines. These T/R modules are all fabricated on semiconductor substrates, with the most typical being silicon (Si) and gallium-arsenide (GaAs) for low and high-frequency MMICs, respectively. Not only are these substrates necessary for realization of advanced T/R modules, they are also PC by their very nature. Photoconductors are materials that create electron-hole pairs from incident optical photons. Therefore fabrication of high-speed transmission lines on semiconductor substrates yields high-speed PC switches.

The generation of electron-hole pairs results in the creation of a solid-state plasma, since this plasma exists in the solid state (i.e., in the semiconductor). The interaction of the optically-generated solid-state plasma with a propagating microwave signal on the high-speed T/R transmission line is the key to our system. We intend to use this solid-state plasma/microwave interaction to attenuate the amplitude of the propagating signal. The preliminary basis for this work has been demonstrated earlier [2-4]. However, to date a practical attenuator for radar applications, and more particularly phased array antenna control, has not been suggested using this PC technique.

We propose that electronically-controlled rf and/or microwave attenuators be removed from the phased array antenna T/R modules. By using the pre-existing high-speed PC switches, we propose that these embedded PC switches be optically excited by laser illumination delivered either by free-space bulk optics and/or individual fiber-optic cables. These laser beams shall be individually addressable by use of several optical control schemes. Although many such schemes exist, and are considered a part of this system, two techniques should yield proper operation: the use of vertical cavity surface emitting lasers (VCSEL), whereby each laser diode (LD) is electronically addressable, or the use of spatial light modulators (SLMs), like the liquid crystal array (LCA) techniques such as those demonstrated by Riza [4]. Here, the VCSEL can be either directly or externally modulated, while the LCA technique achieves laser beam modulation by directly addressing individual pixels on the LCA, whereby each pixel controls a single laser beam. A third technique is the use of optical fiber delivery from a single high-power solid-state laser. Here the cables can be made individually addressable by splitting the single laser beam into a number of individual fibers equal to the number of phased array antenna T/R modules. These individual beams may then be controlled by electro-optic (EO) control elements, such as acousto-optic (AO) modulators, two-dimensional SLMs, or bulk EO deflectors. In any event, the control of the laser beam intensity must be such that each beam is individually controllable so that each T/R module receives a pre-determined level of optical power to provide the necessary rf signal amplitude attenuation when the PC switches are activated.

The optical energy delivered by the individual optical fibers then controls the solid-state plasma density within the high-speed transmission line: the stronger the optical intensity, the more dense the plasma, and so greater the attenuation. Thus the actual attenuation level is directly controlled by adjustment of the optical intensity. This offers several advantages for radar phased array antenna control applications:

(1) Higher speed control due to the higher propagation speed inherent with optical fibers and the fast switching speed of laser diodes;
(2) high-density phased array antenna control, due to reduced weight and size of optical fibers;
(3) lower cost due to large-scale ease of distribution via optical fiber control networks;
(4) increased control and antenna carrier signal-to-noise ratio immunity since the control mechanism is optical.

4. Optical Control Techniques and Systems for N-bit Microwave Attenuation

Figure 1 shows a block diagram of the radar system front end (typically referred to as the radar transceiver for a radar using the same antenna (ANT) for both transmit and receive) showing the N-bit PCS attenuator, the phase shifting element, and standard transceiver componentry (high power amplifier (HPA), low-noise amplifier (LNA), and circulators to direct the transmit (T) and receive (R) signals. Connection is made to the antenna as shown, and to the receiver and transmitter sub-systems via the input port.

Fig.2 shows a simple free-space optical configuration of the N-bit O/E attenuator concept used for attenuation control. A fiber-pigtailed laser diode output is launched from the fiber pigtail into free-space using a collimating lens. The collimated free-space beam is then vertically polarized and passes through a half wave plate (HWP) that rotates the polarization by 45 degrees, which yields an output beam of both horizontal and vertical polarization at the outputs of the polarization-preserving beam splitter (PBS). Thus, the beam sent through the PBS forms two beams of equal intensity.

One beam is directed onto the gap of a Si:CPW-PCS using a rotatable mirror and focusing lens. The other beam is sent through a second HWP and re-split again in a second PBS. These two final beams are also directed onto the Si:CPW-PCS switching gap. Using the HWPs, the intensity of all three beams can be equalized so that the intensity of each spot (A) is uniform. Thus, three spots yield a 4-level "2-bit" attenuation scheme. As described later, if the spots are designed to yield different attenuation levels, an 8-level or 3-bit attenuator can be formed using the three control beams. The microwave signal to be attenuated flows from the input port P_1 through the Si:CPW-PCS to the output port P_2. The optical spot A interacts with the propagating microwave signal and, through classical plasma attenuation [3], attenuates the signal. The Si:CPW-PCS has been described earlier [2,4], but in summary consists of a coplanar waveguide (CPW) geometry used to fabricate the switch contacts which, having been placed on a suitable PC substrate serves to form the PCS. Here silicon is used, hence the designation Si:CPW-PCS.

Fig. 3 shows another optical control method for microwave attenuation and control. Here the free-space optical components have been replaced by an optical fiber splitter and an external EO modulator. The EO modulator provides both individual beam amplitude equalization, and switches N-beams on at any particular time to achieve N-levels of attenuation. In this case, each beam's optical power is optimized to give the highest (saturation mode) microwave signal attenuation corresponding to the particular illuminated position on the microwave transmission line. Thus, if a single spot is designed to give an attenuation of 10 dB, then a cascade of seven similar power spots will give a total attenuation of 70 dB when all spots are on. In a different design that yields an N-bit operation, the N beams are designed to result in different attenuation levels. For example, for a 3-bit design that should give a total of eight attenuation levels, the spatially/powerwise different beams 1, 2, and 3 should cause individual attenuations of K, 2K, and 4K dBs, respectively, where K in dB is the smallest attenuation control possible with this binary N-bit design. Just as in Figure 2, these individual beams impinge on a PCS gap, again shown here as the Si:CPW-PCS. The EO modulator consists of two crossed-polarizers and a LCA. This arrangement permits both beam amplitude equalization and, due to the high contrast ratio of modern-day LCAs [5], the beams may be switched on or off to achieve N-bit operation (i.e., N = 1 means only one beam passes through the LCA, N = 2 means two beams, and so on). Not shown in this figure is the LCA driver electronics, which here we assume to be part of the LCA.

Fig. 4 shows essentially the same system design, only here the fiber-pigtailed laser diode and associated driver (not shown) have been replaced with a 2-D laser array such as a VCSEL source. The VCSEL structure contains many individual laser diodes, all individually addressable through the use of the 2-D VCSEL driver and driver/VCSEL interface. The choice of which lasers (i.e., VCSEL "pixel") to turn on or off is defined by the user via the N-bit controller, which is either manually controlled, or most likely, computer controlled by the radar system's dedicated software. This permits direct modulation of each individual VCSEL, and, hence, bit, in the EO attenuator. This optical source configuration has several primary benefits, namely, reduced cost (EO modulator, bulk optics, etc., are expensive), higher reliability via monolithic VCSEL driver/array technology, and larger modulation depth than EO modulators, resulting in superior performance. Finally, the beam quality of VCSEL pixels is high quality (i.e., uniform round spot), and the difficulty of coupling/focusing highly divergent and astigmatic-edge coupled laser diodes to form the spot A on the Si:CPW-PCS switching gap is reduced.

Figure 5 shows a detailed description of the N-bit PCS attenuator. Here the optical source is identical to the one described in Figure 4. The only difference with Figure 4 is the redesign of the attenuating medium, from the Si:CPW-PCS to the more application-specific N-bit PCS. Here the same principle of operation that held for the Si:CPW-PCS is utilized: a switching gap is located between the PCS conductors, which have been fabricated on a PC substrate. The only difference is that here the conductors are made using a coplanar stripline geometry (i.e., two conductors as opposed to three for the CPW structure used in Fig.4). These conductors are designed to yield maximum microwave signal attenuation of signals flowing both from (to) the receiver and to (from) the antenna. This is accomplished as outlined by Saddow et. al [6], by essentially matching the switching gap employed to both the PC substrate used and VCSEL wavelength. Otherwise, the operation of Figure 5 is as described in previous figures.

5. 2-bit Optically Controlled Microwave Attenuator Concept Experiment

To demonstrate the concept of a variable N-bit optically controlled microwave attenuator using the PC effect, the experiment in Fig.6 was set-up in the laboratory. The Si:CPW-PCS used has a 10 μm PC gap between coplanar waveguide contacts. The overall test device length is 1.6 cm and has a measured rf insertion loss of 10 dB at 990 Mhz. Note that much smaller insertion loss can be obtained when the device length is reduced greatly for commercial applications using well designed, small area optical illumination. Detailed characterization of the PCS used in our experiment has been described earlier [2,4,6]. Here, we use the rf attenuation properties of the PCS to form a switched attenuator that can yield optimized attenuation performance. Previously, we had experimentally shown that for a given

optical spot illuminating a certain section of the microwave transmission line, increasing the laser spot power eventually saturates the maximum attenuation level possible. Thus, futher increasing the laser power does not buy one much more attenuation. This is because the attenuation value is approximately an exponential function of the induced plasma density, where the plasma density is linearly related to the spot optical power [2].

In this paper, we propose spatially distributed illumination of the PCS (e.g., using multiple spots) to avoid the attenuation saturation effect. In this way, the PCS can be designed to give higher attenuation. Moreover, if the power of the multiple spots are different and the beams can be independently switched on and off, it is possible to make a switched N-bit attenuator using N beams. Fig.6 shows the set-up to demonstrate a 2-bit attenuator using two control beams. Linearly polarized light at 532 nm from a high power (>50 mW) frequency-doubled Nd-YAG laser is incident on a $\lambda/2$ plate that is used to rotate the plane of polarization of the incident light that then strikes a cube PBS. By varying the angle between the fast axis of the $\lambda/2$ plate and the laser polarization direction, it is possible to rotate the beam polarization, which when coupled with the PBS gives two spatially separated s and p polarized beams with different power levels. Using total internal reflection (TIR) prisms and another PBS, the two beams are redirected toward a 10 cm focal length cylinder that focuses the light on the gap in the PCS. The two spots illuminating the gap are each 10 μm high by 3 mm wide. By slightly shifting one of the prisms, the two spots are positioned side by side on the PCS gap. These beams can be rapidly switched on and off using an optical switch such as a ferroelectric liquid crystal (FLC) SLM with a 10 μs switching time. To demonstrate the switching principle, we use mechanical shutters to block the light when required.

A - 10 dBm level 990 Mhz signal is directly fed to the PCS attenuator device. The output from this device is connected to a spectrum analyzer that gives a rf power level of - 24.4 dBm when no light is incident on the PCS. This 14.4 dB insertion loss is a combination of the PCS loss, along with rf cable and connection losses. For the first experiment, the optical powers in the two control beams are adjusted (using the rotation of the $\lambda/2$ plate) to be roughly equal so that each beam gives approximately the same rf attenuation level. In this case, the level is - 32.3 dBm when either beam 1 (power = 24.4 mW) or beam 2 (power = 18.4 mW) is on. When both beams are on, the reading is - 40.0 dBm. Thus, each beam can induce an attenuation of 7.8 dB, and when both beams are on (power = 42.8 mW), we get a total attenuation of 15.6 dB. Thus, this 2-beam optically controlled microwave attenuation device has three attenuation settings: 0, 7.8, and 15.6 dB. Fig.7 shows the experimental data for this experiment.

The next experiment shows how a 2-bit, 4 level attenuator can be formed using the two control beams incident on the PCS. In this case, the powers in the two beams are adjusted so that we get a binary relationship between the four different attenuation settings, i.e., 0, K, 2K, and 3K dBm, where K is the resolution of the attenuator. In our case, we adjust the beam powers to get: beam 1 (12.7 mW) gives - 30.2 dB reading; beam 2 (28.2 mW) gives - 35.5 dB reading; both beams on (40.9 mW) gives a - 40.0 dBm reading. This means that the four attenuation levels are: 0 dBm (no light), 5.8 dB (beam 1), 11.1 dB (beam 2), and 15.6 dB (beam 1 & 2). Thus, in this case, K is 5.8 dB. For a true binary setting in this case when 3K = 15.6 dB, K = 5.2 dB. Because the two beam spots on the PCS gap are not exactly the same spatially, and the PCS response is not exactly uniform over the length of the microwave waveguide, careful adjusting of optical power and beam shape and position are required to get an ideal binary attenuator. Nevertheless, we have shown an attenuator with approximately a 2-bit performance. Fig.8 shows the experimental data for this experiment. Note that the graphs show a near-linear response, indicating that we are operating at the most efficient/steepest part of the photoconductivity .vs. optical power exponential relationship; also considered optimum from a laser power design point-of view. Fig.9 shows spectrum analyzer readings for the four different levels of the 2-bit attenuator measured at 990 MHz.

6. Conclusion

In conclusion, our system distinguishes itself from previous N-bit attenuators in the following way. We have presented a new method for attenuating the microwave signals using PC switches fabricated in such a geometry so as to permit N-bit operation. This method requires the use of laser light such that individual laser beams are actively controlled using either external modulators or integral laser diode array electronic drivers. Thus we may achieve not only N-bit attenuator operation, but our scheme is inherently faster and of possibly lower cost and weight than conventional all-electronic schemes. By employing VCSELs to perform optically induced microwave signal attenuation, we have suggested how large phased array antennas can be accurately controlled without the need to add additional system cost and weight as our PCS technique utilizes pre-existing PC substrates in the T/R modules.

7. References

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Figure 1. Block diagram of N-bit EO scheme, showing radar transceiver sub-system, attenuation (N-bit PCS attenuator), and phase shifting elements.

Figure 2. Concept setup for 2-bit (or N = 3 bits with different beam powers) EO attenuator, where in this drawing, bits are realized using free-space bulk optics.
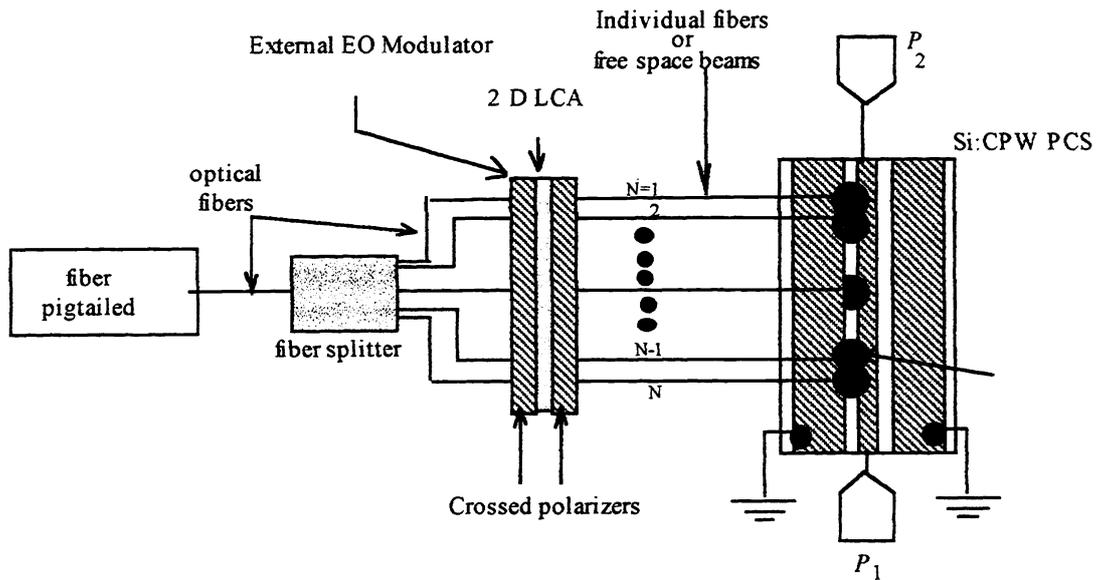
Figure 3. EO attenuator with N bits using 2-D LCA to control each beam. Single fiber-pigtailed semiconductor laser diode is again used as optical source.
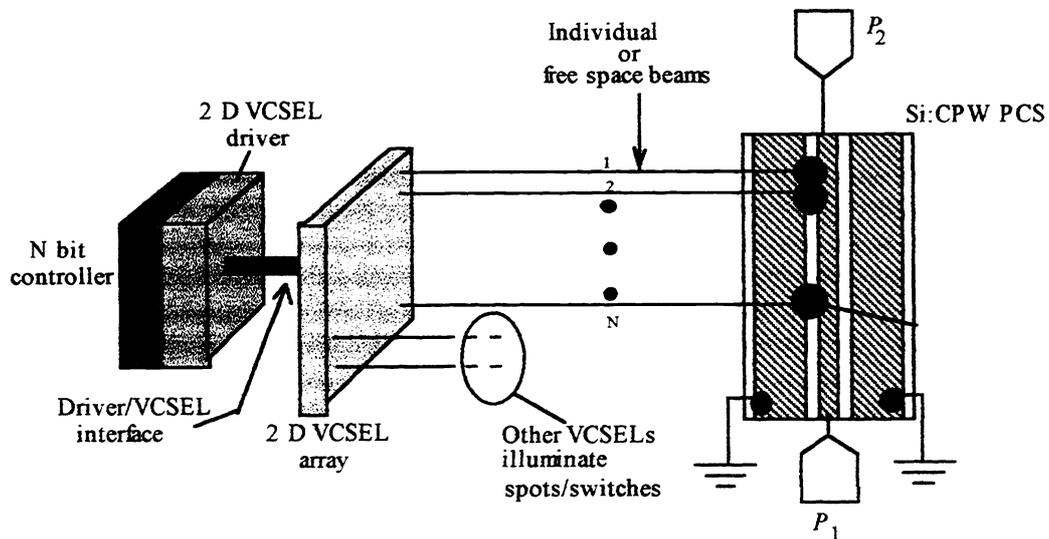

Figure 4. N bit EO attenuator, only this time, 2-D array of VCSELs is used to activate each bit (shown is case of directly addressable VCSEL array, where optical intensity per beam is thus controlled by VCSEL drive current).

Figure 5. N-bit EO attenuator scheme showing detailed view of N-bit PCS atttenuator, realized using 2-D VCSEL array to control each beam and N-bit PCS. Note only 1 row of the EO attenuator and phase shifter elements shown.

Figure 6. Experimental set-up to demonstrate concept of optically controlled variable switched microwave signal attenuator. System is tested as a 2-beam/3 level and 2-beam/4 level:2-bit optically controlled attenuator.
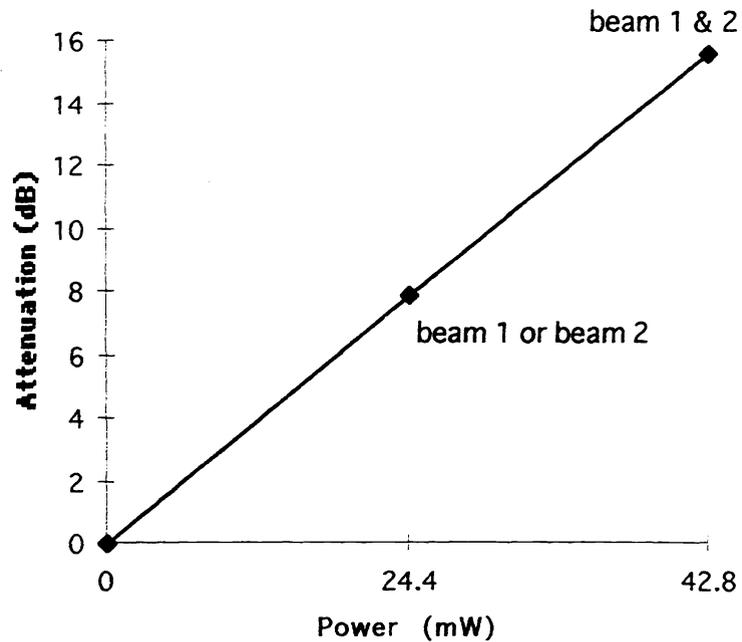
Figure 7. Experimental results from 3-level optically controlled attenuator showing three different attenuation data points. In this case, both beam 1 and beam 2 are designed to give same attenuation.
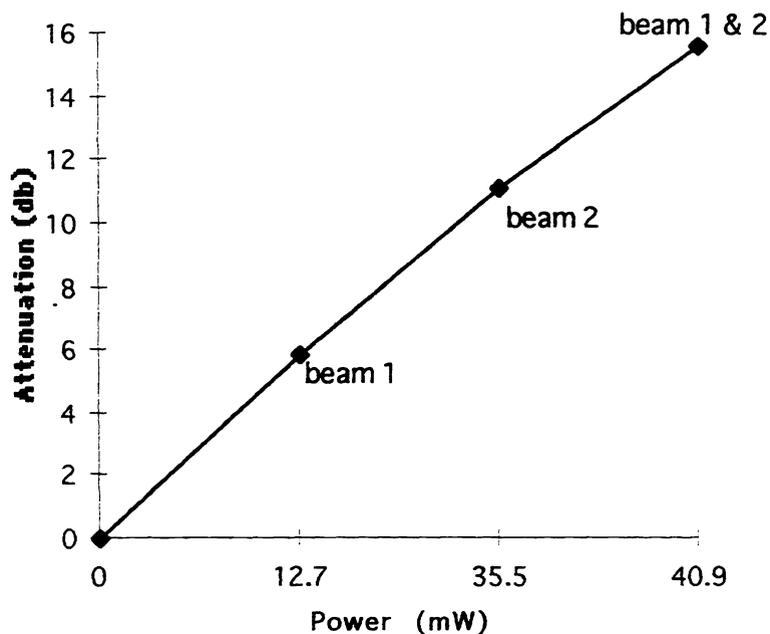

Figure 8. Experimental results from 4-level (or 2-bit) optically controlled attenuator showing four different attenuation data points. In this case, beam 1 and beam 2 are designed to give different attenuation levels.
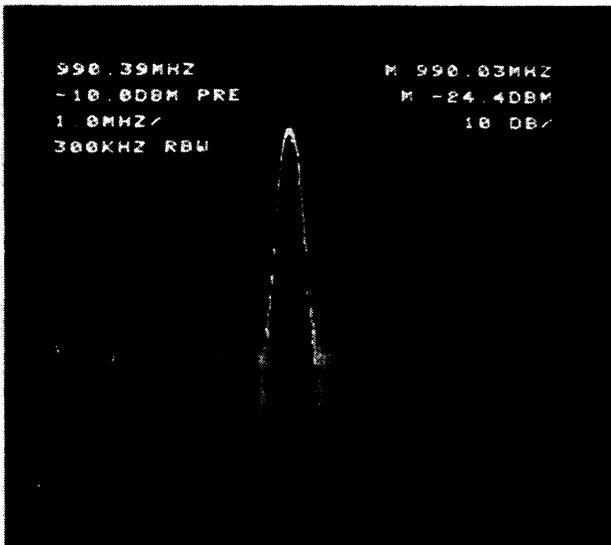
Fig.9 shows spectrum analyzer readings for the 4 different levels of the 2-bit attenuator measured at 990 MHz.