OPTICALLY CONTROLLED MICROWAVE DEVICES AND CIRCUITS

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SUMMARY

There is a growing interest in optically controlled microwave devices and systems. This paper is concerned with two experiments in this emerging area. The first describes the design, fabrication and application of optically controlled microwave PIN diodes. The utilization of these devices for phase-shifting and switching at X-band was demonstrated. The second experiment involved the optical tuning and indirect optical injection locking of a X-band dielectric resonator oscillator. A locking range of 400 KHz was achieved utilizing a third harmonic.

INTRODUCTION

There has been continued and increasing interest over the past few years in the control of microwave devices and circuits with optical signals (1,2). This interest has been generated partially by the availability of new, high speed, electrooptic devices (diode lasers, modulators, switches, etc.) and by the development of more sophisticated microwave systems which require better and faster control. The monolithic integration of electrooptic and microwave devices to produce self-contained components and subsystems to perform such microwave control functions as switching, limiting, phase-shifting, phase-locking, oscillator tuning and amplifier gain control is feasible. Optical control of microwave systems may lead to new applications such as light weight and low cost airborne phased array radars, which are difficult to achieve with present technologies.

The advantages of optical control include: short response time, high modulation rates, inherent high DC and reverse signal isolation, compatibility with optical fiber communication systems, immunity to electromagnetic interference and low cost.

Two experiments are reported. The first is concerned with optically stimulated microwave PIN diodes, the second with optical tuning and injection locking of a dielectric resonator oscillator (DRO).

OPTICALLY CONTROLLED PIN DIODE

The fundamental concept for optically controlled junction devices is to use the optical illumination as an additional terminal through which the device behavior can be controlled. In the case of a PIN diode, which is a two terminal device, the optical port acts as a third terminal affecting the resistance and the capacitance of the device.

PIN device design and fabrication. Microwave devices and monolithic circuits are fabricated from high resistivity materials (GaAs, Si) which are also sensitive to optical excitation. The most difficult task in the optical control of microwave devices has been the efficient coupling of the light to the active region. To overcome this problem a modified microwave PIN diode with an optical port was designed, as shown in Fig. 1. The device is fabricated from a high resistivity ($3\text{-}5\times10^3$ ohm-cm) N type Si wafer. The 140 μm Si wafers were doped with Boron and Phosphorous on opposite surfaces. Junction depths of 23 μm for the P^+N junction and 20 μm for the N^+N junction were established through two-point spread-resistance and SIMS measurements.[1]

The wafers are implanted on one side with ^{11}B atoms and on the other side with ^{31}P atoms to form the P^+ and N^+ contact layers respectively. In order to increase light coupling to the device, windows were etched at the center above the P^+N junction. This way, the optical input could penetrate to the active layer, where it is absorbed. The control of the etching process is particularly crucial to device performance since it is desirable to get close to the junction without adversely effecting it.

It should be noted that this fabrication technique is compatible with proven monolithic microwave integrated circuit processing techniques and furthermore, that IMPATT diodes could be prepared in a similar fashion.

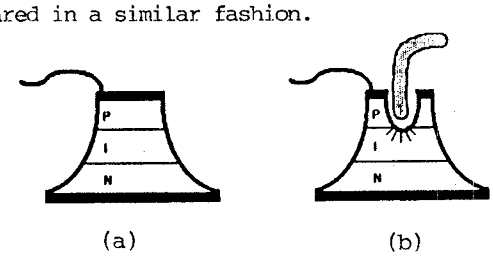

Fig. 1. Conceptual representation of microwave PIN diode; (a) before and (b) after modification with optical input.

Low frequency characterization of the PIN. Low frequency measurements were performed on the devices to determine if the capacitance and resistance of the PIN is indeed a function of optical input, to verify that they behave as three terminal devices. The variation of capacitance and resistance as a function of biasing voltage at different light intensities was measured on a 110 MHz bridge (Fig. 2). The diode, as expected, behaves like a three terminal device. When the diode is not illuminated

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it behaves like standard microwave PIN diode. On the other hand, when the reverse biased diode is illuminated from the top, capacitance increases by 25% at light intensities of 1W/cm^2, accompanied by a reduction in shunt resistance. These changes are caused by the optically generated carriers in the intrinsic region. The dependence of the capacitance and shunt resistance on the wavelength of the incident radiation was also investigated. The results indicate that the wavelength dependence is simply governed by the absorption coefficient. Based on these initial measurements one can predict that by varying the device parameters (geometry and material) and operating conditions (biasing potential), the optically stimulated PIN would have a faster response time, greater sensitivity and more versatile performance than conventional microwave PINs.

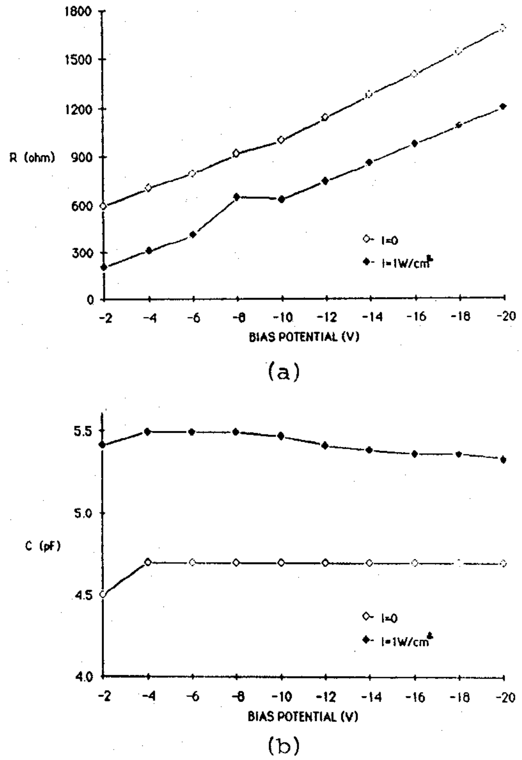


Fig. 2. Bridge measurement of PIN diode at 110 MHz; variation of (a) resistance and (b) capacitance vs. reverse bias potential under illumination (1W/cm^2) and dark.

Test of the optically controlled PIN at X-band. The optically stimulated PIN diodes could function in microwave circuits as phase-shifters, attenuators, limiters, modulators and switches. Two experiments were performed to asses the potential of the device for microwave applications. In the first experiment the diodes were incorporated into a coplanar MIC phase-shifter configuration, as shown in Fig. 3. The diodes were reverse biased at 20 V, illuminated by a white light source (1W/cm^2), which caused a phase-shift that was monitored on an error corrected network analyzer. A linear phase-shift of over 10^{o} with a 15% bandwidth at 10 GHz was observed, as shown in Fig. 4. The phase-shift varied directly with illumination. To obtain a high frequency equivalent circuit of a three terminal PIN

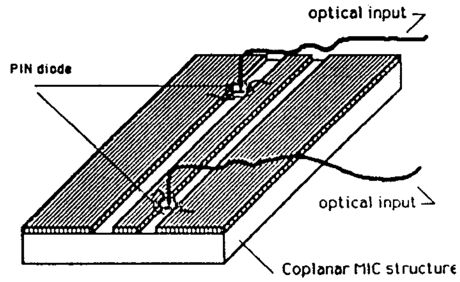


Fig. 3. Conceptual representation of optically controlled MIC phase-shifter.

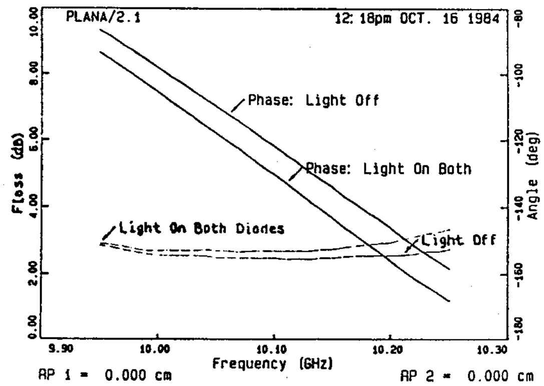


Fig. 4. Network analyzer measurements of phase-shifter (reverse biased at 20 V) dark and under illumination (white light 1W/cm^2).

diode, its S-parameters were fitted to a standard PIN equivalent circuit. The elements of the circuits were found using Super-compact (CAD) optimization routines. These results were extended to a phase-shifter optimization routine to determine how to improve overall performance. The results of the optimization indicate that the limiting factor in the performance of the phase-shifter is the initial shunt capacitance. This is responsible for the high insertion loss. The initial (dark) shunt capacitance can be minimized by reducing the size of the diode, which would lead to enhanced phase-shifter performance.

In the second experiment, the PIN diode was used as a switch in a MIC Gunn oscillator circuit, as shown in Fig. 5. When illuminated, the PIN bridges the gap between the resonator and the stub, thus changing the reactance of the circuit and hence its resonant frequency (3). Using this approach, the oscillator was tuned up to 60 MHz at .5 V biasing,

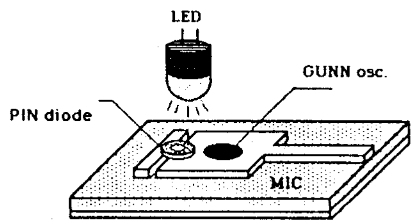


Fig. 5. Conceptual representation of optically tuned Gunn oscillator circuit by PIN switch.

and frequency modulated at 300 MHz as shown in Fig. 6. This circuit was also analyzed and an optimization procedure is presently being developed.

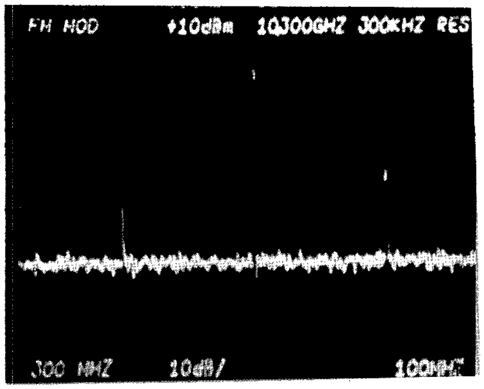


Fig. 6. Narrow band FM spectrum of Gunn oscillator (Horizontal scale 100MHz/div).

Discussion. An optically controlled microwave PIN diode was fabricated from high resistivity N-type Si and characterized at low frequencies (110 MHz) and at X-band. In particular, the optically controlled microwave PIN diode was implemented as a phase-shifter and switch in microwave circuits. The experimental results of the modified microwave PIN diode confirmed that the optical port behaves as a control terminal. The results also indicated that the device has potential applications in a variety of microwave circuits. These experiments provided important information linking device design to performance and thus provide direction for further improvements.

OPTICALLY CONTROLLED DRO EXPERIMENTS

One proposed application of optically controlled microwave systems is an airborne phased array antenna (1), consisting of spatially distributed individual MIC oscillators (array elements) which are synchronized by a modulated optical signal via a fiberoptic distribution network. This technique offers potential advantages in electrical isolation, speed, immunity to EMI, cost and a very significant reduction in size and weight. The main difficulty in achieving such a system is a small optical injection locking range, primarily due to two factors, low modulation depth of lasers at high frequencies and poor optical coupling efficiency into the active region of the microwave devices (4-6). To overcome some of these limitations an alternate approach is considered here. Results of employing the combined effect of indirect optical subharmonic injection locking and optical tuning of the DRO for extended locking range are presented below. A DRO oscillator circuit was selected for this study; DROs provide good temperature stability and spectral purity at a reasonable cost which makes them desirable for many applications. On the other hand, the DRO is an inherently high Q circuit and therefore requires more injected power to attain a reasonable pulling range.

Experimental procedure. The concept used in our experimentation is shown in Fig. 7. To enhance the range of the injection locked oscillator two optical signals are utilized. The DC optical signal illuminating the photosensitive element on top of the dielectric resonator serves the purpose of tuning the DRO frequency to the proximity of the master oscillator. In essence, the optical illumination replaces the mechanical tuning screw (3,7). With this technique a tuning range of nearly one MHz has been demonstrated using a 1 mW IR LED source. (Up to 12 MHz of tuning was attained at optical flux of 1 W/cm^2.) The optical tuning is a linear function of light intensity, it has no adverse effect on the DRO performance and it is extremely fast (7). The second optical signal, the AC signal modulated by the master oscillator, is coupled to the DRO circuit via a high-speed PIN diode photodetector. This method is considered to be an indirect optical injection locking scheme because the optical signal is first converted into an electrical signal by the PIN and then injected to the FET.

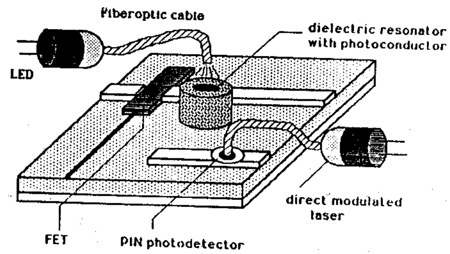


Fig. 7. Conceptual representation of DRO's optical frequency tuning and indirect optical injection locking.

Indirect optical injection locking of oscillators is, in principle, identical to electrical injection locking. This approach has two desirable features. First, it takes advantage of good optical coupling efficiencies of the high-speed photodetector (large active region). Second, it utilizes the nonlinearity of the PIN device to generate higher order harmonics from the laser output, thereby making injection locking possible at higher frequencies. Due to the optical frequency tuning capability and enhanced optical coupling to the PIN, improved injection locking can be attained.

A commercially available X-band (10.8 GHz) DRO with an external Q of 1000, manufactured by Mitsubishi (8), was used. A packaged laser diode and optical PIN detector manufactured by Ortel were used for the optical components. These particular devices were not equiped with fiberoptic pigtails, which resulted in considerable optical losses (over 10 dB). The laser was modulated at 3.6 GHz and the third harmonic output signal of the PIN was injected to the DRO circuit using a three port circulator. The output of the DRO was monitored on a spectrum analyzer as shown in Fig. 8.

A pulling range of 400 KHz was observed, which is in good agreement with the theoretical prediction for the measured injected power level. The spectra of the unlocked oscillator and injection locked oscillator are shown in Fig. 9. The reduction in FM noise is evident.

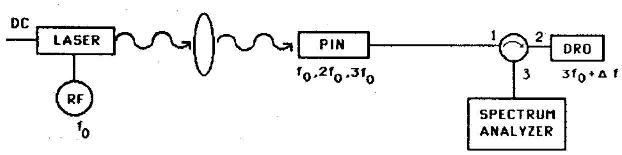
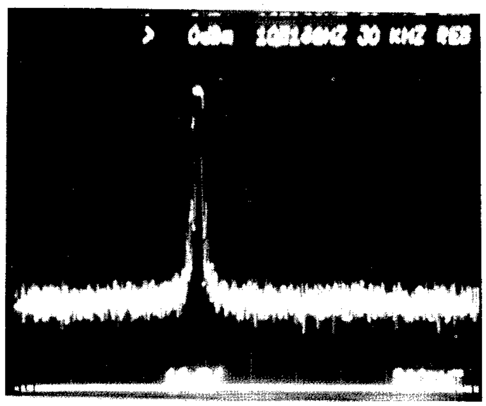
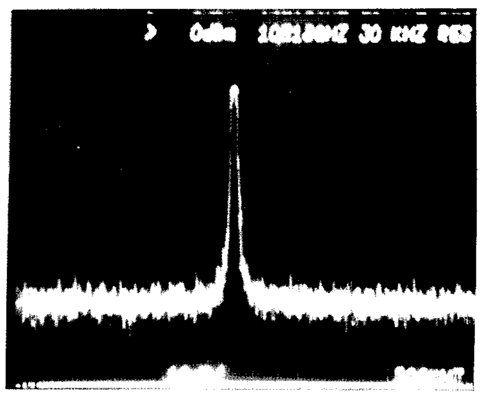


Fig. 8. Experimental set-up.



(a)



(b)

Fig. 9. Spectra of the DRO in injection locking experiment representing a 400 KHz pulling range, (a) begining of locking, (b) getting of locking.

Discussion. The experiments proved the feasibility of indirect subharmonic optical injection locking of DRO oscillators at X-band. The combined effect of optical tuning and injection locking yielded a respectable locking range. Optimization of the experiment has commenced. In particular, present work includes improvement of the optical link between the laser and the PIN detector, integration of the PIN into the MIC oscillator circuit and simultaneous injection locking of several spatially distributed oscillators.

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