OPTICS FOR MICROWAVE APPLICATIONS

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SUMMARY

Advances in Laser technology, high speed modulation of light and optical interaction with solid state microwave devices have demonstrated the potential of optics for microwave applications such as RF spectrum analysis, fiber optic RF links and delay lines, phased array steering, microwave power control devices etc. This paper brings into focus current developments in the general area of optoelectromagnetics.

INTRODUCTION

Microwave and RF applications of optics can be subdivided into four basic categories:

a) Microwave modulation of optical sources
b) Interaction of optical and RF waves
c) Optical control of solid state microwave devices
and d) Optical fabrication technologies for millimeter waves devices

Microwave Modulation of Optical Sources

High frequency modulation of optical sources is essential for fiber optic RF links and delay lines. Optical links may serve as a direct replacement for short coaxial lines or multigigabit trunk lines, intra satellite guided wave switches, antenna remoting, phased array antenna feeds, among other applications.

Optical sources may be modulated either directly by modulating the bias current of the laser diode or by means of an external modulator. Direct modulation is easy to implement but the frequency of modulation is limited below the relaxation resonance frequency of the device. The modulation bandwidth is given by (1)

$$B_M = \frac{1}{2\pi} \left(\frac{A\,po}{\tau}\right)^{1/2} \qquad (1)$$

where A is the optical gain coefficient, po is the steady state photon density and τ is the photon life time.

Photon life time is reduced by shortening the laser cavity length, limited by the thermal effects due to excessive heating when a diode is driven at high current densities. The gain coefficient, A, can be increased by simply cooling the device. An improvement in gain coefficient by a factor of 5 is possible when the device is cooled from room temperature to 77° K. The photon density may be increased by increasing the laser bias current. Unfortunately, this is associated with higher optical power densities which can cause catastrophic mirror damages in the cavity. Window structure lasers have overcome this problem to a large extent.

Package parasitics have to be minimized for high frequency modulation of the laser diode. This has been done by fabricating the device on a semi-insulating substrate (2). The dynamic response of a direct modulated laser can be analyzed using a circuit model or by experimentally measuring the characteristics in a temperature stabilized text fixture (3). The equivalent circuit of the laser at RF bias port can be incorporated in a microwave circuit analysis program to match microwave driver/amplifier with the low impedance of the optical device.

For greater modulation bandwidths, a LiNb03 travelling wave modulator in Mach-Zehnder configuration has been demonstrated up to 17GHz (4). Photorefractive effects in the substrate material limit its power handling capability to about 100mW at 0.83um and an order of magnitude better at 1.3um optical wavelength. Propagation as well as input/output fiber coupling losses result in still less power launched into the optical RF link limiting its use only when it is a must.

RF Links

Fiber optic transmission of RF signals is inherently, low loss, wideband, secure and immune from electromagnetic interference. In a practical link design, one takes into account modulation, demodulation and coupling losses.

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Typically, a fiber optic RF link of less than 150 feet long operating at 5 GHz is less lossy than a coaxial cable based system. The loss advantage become much more apparent at higher frequencies. The frequency response of the link is primarily governed by the responses of the laser diode and the detector. A GaAs Schottky photodiode on a semi insulating substrate has provided a 3 dB bandwidth in excess of 100 GHz (5). At frequencies near laser resonance, the excess noise distribution of the laser diode is dominant limiting the SNR of the link.

Delay Lines

A silica fiber has a propagation delay of approx. 5us/km while the propagation loss may be 1dB/km or less. A practical delay line design, however, will have to take into account additional losses due to source-to-fiber coupling and bending losses when a long fiber is wound into a coil. GRIN rod microlenses have been used to minimize coupling losses. The important characteristics of a delay line are similar to those of the RF link. Additional requirements may be low temperature coefficient of delay and large time bandwidth product. The thermal characteristics of the delay line depend upon the temperature coefficient of the dielectric material,(a few ppm/°c positive) and the thermal expansion of delay line, (0.5ppm/°c to 10ppm/°c for fused quartz). Fibers optimized for delay line applications are possible in the near future.

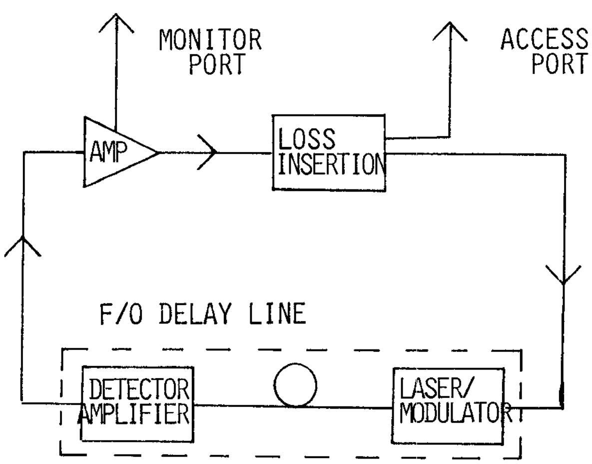

FIG. 1: RECIRCULATING DELAY LINE SCHEMATIC

The concept of fiber optic delay line is easily extendable to tapped delay lines and recirculating delay lines. Tapped delay lines may be fabricated using access couplers along a long fiber or by using separate fibers for each time delay required. A recirculating delay line, shown in fig. 1 minimizes the requirements of a very long fiber (hundreds of kilometers for millisecond delays) and the hardware for some applications such as moving target detection and frequency memory loops. An important design considerations is that the input signal pulse width has to be less than the delay times per pass to avoid pulse overlapping. Preliminary results for a single mode fiber 1GHz-1ms recirculating delay line are promising (6). Fiber optic delay lines promise higher operating frequencies, wider bandwidths and greater accuracy in configuring beam forming networks to feed individually the correct amplitude and phase to all elements of a multiple beam antenna or a phased array.

RF/Optical Interaction

Acousto optic techniques offer the potential of a high probability of intercept receivers even in the presence of simultaneous signals. Additional attractive features of an A/O receiver are its size, weight, processing complexity and cost (7). In a A/O Bragg Cell receiver the RF channelizing is performed by the interaction of a collimated laser beam with a travelling acoustic wave as shown in Fig. 2. The presence of N signals, simultaneous or otherwise, results in N deflected spots, depending upon their frequencies, which can be detected by placing a photodetector array at the output plane. The important design considerations for an A/O receiver are the instantaneous RF bandwidth, operating wavelength, frequency resolution, efficiency, optical scatter, intermodulation products and the power handling capability. The individual components of the receiver are optimized based on the detailed analysis of their effect on the entire system design. For example, a short optical wavelength is desirable for bandwidth and efficiency but it is incompatible with minibench technologies since laser diodes below 800nm are not readily available. Similarly, a high velocity mode or a large interaction length may increase bandwidth but both factors compromise efficiency.

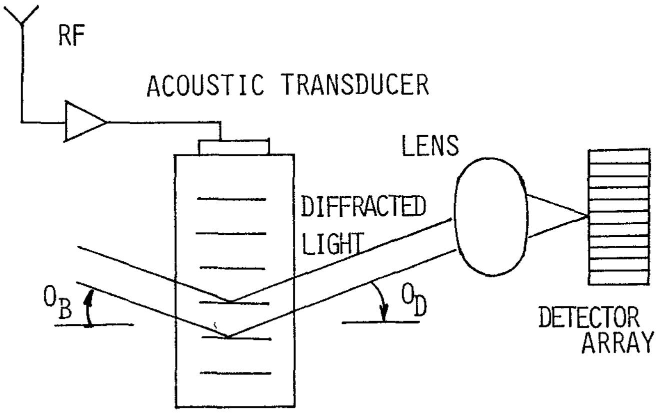

FIG. 2: BRAGG CELL SPECTRUM ANALYSIS

The low efficiency may be compensated by increasing RF power but it is limited by nonlinear acoustic effects in the substrate material. To date, the demonstrated dynamic range of the A/O receiver has been disappointingly low especially in the presence of simultaneous signals. In addition, there is a serious degradation in performance when very short pulses ($\sim$ 100nsec) are being detected. Integrated optic spectrum analyzers (IOSA) using surface wave RF transduction have been limited in RF bandwidths. In addition, it has been extremely difficult to fabricate near perfect geodesic lenses. Bragg cells utilizing bulk acoustic waves have the potential advantage of large bandwidth at higher frequencies of operation. Promising bulk bragg cell results have been obtained using birefringence and shear wave propagation. These are :BW:2-4GHz and efficiency 12%/W at 6328A reducing to 1.4GHz bandwidth and 6.5%/W efficiency at 8300A. The device is capable of 3MHz frequency resolution and a time bandwidth product of 600 (7). Further optimization is possible by rotating the crystal in 3-space to find matching condition which reduces fo in eq2 while maximizing the A/O figure of merit. Two techniques which promise a better Bragg cell receiver are the phase matched array transducers (8) and heterodyne detection (9). Dynamic ranges up to 58dB have been achieved by heterodyning the undiffracted light and the frequency shifted diffracted light through a Mach Zehender interferometer configuration. An alternate scheme using separate Bragg cells, one driven by the unknown RF and the other by a known LO, has reported minimum detectable power of about 1 pico watt ($\sim$ 75dB dynamic range) (9).

$$f_o = (V/\lambda)\sqrt{\eta_1^2 - \eta_2^2} \qquad (2)$$

Optical Control of Solid State Devices

Optical illumination of microwave devices promise ultimate speed and effective control of high power highly nonlinear oscillators eliminating the need for presently used complex and expensive means of stabilization. The injection of light is like introducing an extra terminal which has inherent optical isolation, eliminating the need for any unwanted decoupling structure. Light has been used to phase lock and control microwave generation avalanche diodes, dielectric resonators, injection locking of MESFET oscillators, gain control amplifiers etc.

The laser light controls the operation of a microwave generation device by generating photo induced carriers in the active region. Both, the density and the distribution of the carriers affect the device operation. It is important that most of the incident light is coupled into the active region. Light coupling is enhanced (efficiencies up to 50% demonstrated) by optimizing the optical wavelength and the device bias voltage (10).

The performance of GaAs FETs under optical illumination is of interest to be able to vary FET's dc characteristics, to adjust the gain of an amplifier, to tune a FET oscillator using very low optical power (microwatts) and for high speed optical detection. Active region of the MESFET, the buffer layers and the device substrate absorb light through the gaps between the gate and source and between the gate and the drain regions. Optical absorption produces free carriers in the device material resulting in a change in the relevent parameters of the FET. Photovoltaic and photoconductive effects are represented by variable elements in the device equivalent circuit (11). An external matching circuit can be optimized to exploit the change in device parameters for each application. For example, the change in MESFET transconductance, gm, is used to vary the gain of an amplifier. Gain variations up to 20dB have been observed when the device gate is biased close to pinchoff with only a few microwatts of optical power. FET oscillators have been tuned (10% tuning range at around 10GHz) by adjusting gate-to-source capacitance under illumination (11). Although not fully understood, FM noise performance of FET oscillator has been observed to improve with optical illumination.

Optical injection locking of an oscillator is possible when the light incident on the active region of the FET is modulated at a frequency close to the frequency of the free running oscillator or a suitable subharmonic. For a typical FET the locking range is of the order of a few MHz but it can be increased by more efficient coupling of the modulated light into the device.

Extension of these techniques using fiber couplers or fiber bundles may find acceptability in active phased array radars and other applications where simultaneous locking of a large number of sources is required. Additional applications may include interfacing optical and microwave networks in communication systems, synchronization in monolithic microwave or millimeter wave circuits.

Optical Fabrication/Techniques

Dielectric waveguide techniques commonly developed for optical circuits have been modified for use in millimeter wave applications. Millimeter wave components fabricated using dielectric waveguides resemble more microwave circuits than their optical counterparts. Circuit layout is important to minimize radiation losses and to maximize performance. Typical millimeter wave components are fabricated using higher dielectric constant materials than those used in optical design. Image quides, insulated image guides and inverted strip dielectric waveguides are among the configurations most commonly used for millimeter wave circuits (12). Filters and leaky wave antennas have borrowed grating structure techniques from optical design. The attractive feature of a grating type leaky wave antenna is that the direction of main beam can be controlled by changing the frequency. Distributed Bragg reflection techiques have provided an alternative to conventional millimeter wave generation techniques using two terminal diodes (12).

Conclusions

Rapid development in lasers, photodiodes, fibers, and integrated optic technologies have entered the microwave and millimeter wave systems, components and devices. The potential advantages of this marriage between the two technologies is likely to benefit most EW and communication systems. There are some fundamental limitation but there exists a large scope for further development from its current level.

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