Optical Generation, Distribution, and Control of Microwaves Using Laser Heterodyne

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Abstract —**Results are presented which demonstrate the optical generation and transmission of a microwave signal by mixing two high-quality optical signals from diode-laser-pumped Nd:YAG ring lasers, resulting in a narrow microwave line width (less than 5 kHz line width at 3 dB and less than −115 dBc/Hz at 300 kHz from line center) and broad microwave tunability (dc to 52 GHz). A III–V semiconductor waveguide with a doping superlattice active region is used to optoelectronically provide 20 dB of amplitude control and up to 5π of phase shift. This approach can be straightforwardly implemented using integrated optics and fiber-optic links for control of phased array antenna elements.**

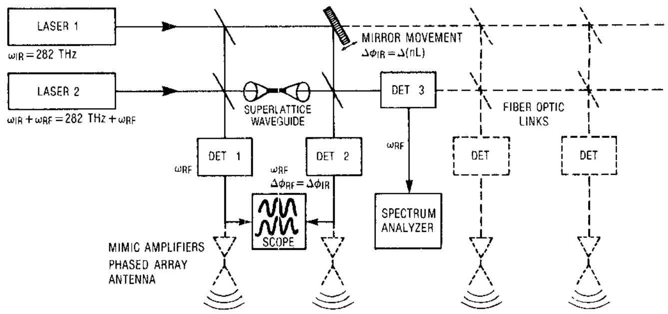

Fig. 1. Optical mixing configuration which provides multiple microwave-modulated optical output beams to control a microwave array. Optical/microwave phase shift is achieved by reflector movement or index change in semiconductor waveguide

I. INTRODUCTION

Optoelectronic communications links are demonstrating microwave bandwidth. Microwave monolithic integrated circuitry (MMIC) is also advancing very rapidly. The fusion of these rapidly advancing capabilities shows much promise for unorthodox solutions to long-standing microwave challenges such as phased array antennas. There is even a potential for conducting this fusion in III–V semiconductor optoelectronics. The use of fiber optical waveguides provides an inexpensive, lightweight, flexible, low-attenuation, low-volume transmission medium that has hundreds of gigahertz of bandwidth and is immune to electromagnetic interference. However, the application of these techniques becomes progressively more difficult as the microwave frequency is increased. This paper reports the use of heterodyne techniques [1]–[3] utilizing two ultrastable Nd:YAG ring lasers [4] to achieve nearly arbitrarily high frequency high-quality optical transmission of microwave signals as well as III–V optoelectronics means of phase and amplitude control of these signals in integrated optics [5].

II. OPTICAL GENERATION OF MICROWAVES

Modulation of an optical carrier at a high frequency can be achieved by the direct modulation of the current applied to a diode laser source or by an optical modulator external to the laser. However, direct modulation of the laser may introduce destabilizing transients and harmonics in the laser output, and diode lasers still have laser line width and stability limitations. External modulators involve coupling effects to the laser. Both approaches become progressively more difficult to implement as the desired modulation frequency increases, and phase adjustment of such optically transmitted microwave signals by optical means is challenging.

Another approach that can optically transmit a high-quality microwave signal is the superposition of two high-quality continuous wave single-frequency optical signals which differ in frequency by the desired microwave modulation frequency. The mixing of these two signals on an optical square-law detector will provide the difference frequency as the output of the detector. There is, in theory, no limit to the magnitude of the difference frequency that can be achieved. The frequency-limiting factor is then the optical detector frequency response. Optical detector response frequencies as high as 100 GHz have been demonstrated [6]. Even higher modulation frequencies may be detectable by using one element as both an optical detector and a mixer [7]. The difference frequency can be of extremely high quality if the optical sources are of high quality individually, or if they are coherently coupled to each other [1]–[3], [8], [9]. This mixing approach to microwave modulation also offers an attractive means of phase and amplitude manipulation, which will be discussed in the next section.

For our optical mixing work, we use high-performance single-mode monolithic Nd:YAG crystal ring lasers (up to 3 mW each) optically pumped by diode lasers [1], [4], [10]. The special features of the design of these lasers result in a highly coherent single-mode emission at 1.06 μm (282 THz) that is temperature tunable over as much as 100 GHz and is highly resistant to optical feedback and laser coupling. Similar performance is achievable at a 1.3 μm wavelength with different Nd:YAG absorption and lasing transitions. Fig. 1 shows the optical mixing configuration (as well as other components to be discussed below). The two optical beams are made collinear by means of beam splitters for each output beam combination desired. Indium gallium arsenide detectors having an active element diameter of 20 μm or less are used [11]. Selected detectors provide sensitivity well beyond their estimated 30 GHz 3 dB roll-off point because of the high signal level available. A Hewlett Packard 8566B spectrum analyzer is used for microwave signal analysis. In the future the optical signal manipulation may be achieved with integrated optics and fiber optics. Each output can be routed to the appropriate remotely located optical detector by means of a fiber-optic waveguide.

Fig. 2 shows the microwave difference-frequency tuning achievable by tuning the optical frequency of one of the lasers. The microwave signal amplitude was observed to be constant, except for cable losses, over the calibrated range of the spectrum analyzer (dc to 24 GHz), suggesting some interesting microwave sweeper applications. The tuning curve shows the difference frequency with the two vertical scales corresponding to two different frequency settings of the reference laser. A tuning range in excess of 50 GHz is demonstrated. An external mixer was added to the spectrum analyzer for the high-frequency measurements above 26 GHz. A doubling of the tuning range should be readily achievable by doubling the temperature changes in the lasers. Such lasers are available. The dashed line in Fig. 2 shows the estimated frequency tuning of the Nd:YAG gain line center

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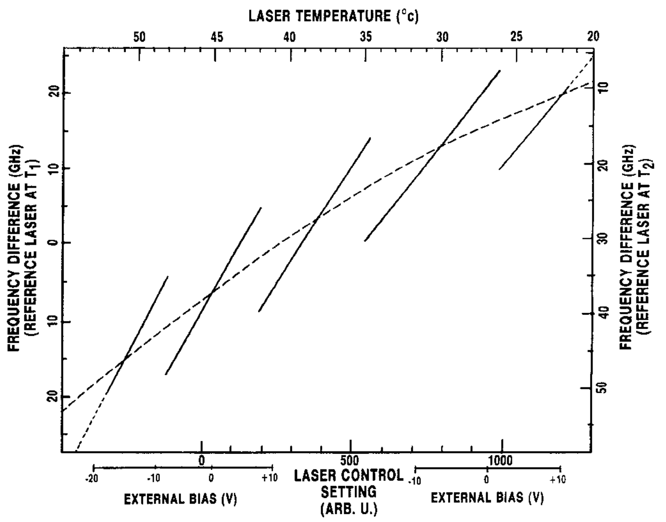

Fig. 2. Difference frequency between two lasers as one of them is temperature tuned relative to the other. Two vertical scales are provided for different reference laser settings.

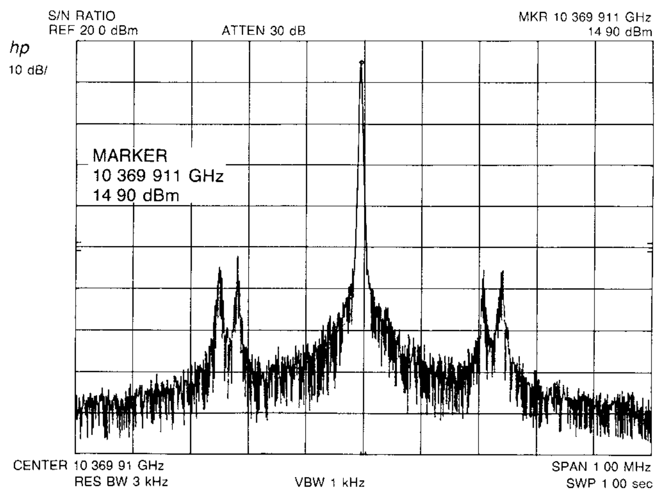

Fig. 3. Short-term frequency content of microwave difference signal at 10 GHz, 100 kHz/div, 10 dB/div

with temperature (1.0 GHz/°C), and the solid line presents the actual difference frequency tuning between the lasers dictated by the temperature tuning of the cavity modes (3.1 GHz/°C). The horizontal temperature scale is approximate and somewhat nonlinear. Settings at which mode hops occur are apparent in the plot. The lasers have a tendency to operate on two cavity modes simultaneously when the laser is close to a mode hop, resulting in a self-beat signal near 14 GHz, but otherwise provide a single pure tunable heterodyne signal. It is of interest to note that a 100 GHz tuning range for these 1.06 μm (282 THz) lasers would be only a 0.04% optical frequency tuning bandwidth.

Fig. 3 shows the short-term power spectrum at 10 GHz with a frequency scale of 100 kHz per division, a resolution bandwidth of 3 kHz and a sweep rate of 100 ms per division. We find the 3 dB line width to be less than 5 kHz when the sweep time over the peak is of millisecond duration. The signal level at 300 kHz from line center is less than -115 dBc/Hz. Sidebands are clearly apparent about 50 dB below the main signal and about 200 kHz to either side of the main signal. These sidebands are due to laser amplitude fluctuations, referred to as relaxation oscillations in the individual Nd:YAG lasers. Laser output leveling circuitry can suppress these sidebands by at least 20 dB [12]. (Relaxation oscillations in diode lasers occur in the gigahertz range.) Our results involve no active laser frequency stabilization. Other researchers have recently reported locking the lasers to a Fabry–Perot cavity [13] or to each other [14] and have achieved 3 Hz and less than 1 mHz 3 dB heterodyne line width respectively. Diode lasers presently have poorer performance with regard to spectral purity, but substantial effort is being made by many researchers to improve their performance for coherent communications applications. Similar results may eventually be achievable with diode lasers.

III. Phase and Amplitude Control

The control of the amplitude of an optical signal and of any microwave modulation superimposed on it is readily achieved optoelectronically. A number of optical modulation schemes have been demonstrated by other researchers and are being aggressively pursued for communications, optical data processing, and other applications. We have demonstrated 20 dB amplitude modulation of an optical signal and the corresponding microwave signal through a doping-superlattice semiconductor waveguide modulator [5].

The phase shifting of a microwave modulation superimposed on an optical carrier is not very straightforward to implement optically in a practical fashion, especially when thousands of parallel channels may be involved and the equivalent of five or more bits of phase shift control are needed for each channel. The optical path length (index of refraction times distance) changes that must be induced are on the order of the microwave wavelength (millimeters to many centimeters or more). This approach does have the merit of providing "time delay" phase shifters: i.e., the phase shifter automatically provides wavelength-dependent phase shifts to correct for wavelength-dependent beam direction from an antenna array. This feature is important for simultaneous, broad-band antenna applications.

An alternative approach is to use optical mixing to achieve the microwave modulation and to phase shift one of the carriers before the mixing is done for each channel. An *optical* phase shift applied to one of the optical carriers results in a corresponding *microwave* phase shift in the microwave modulation [1], [2], [8]. Only an optical path length change corresponding to the *optical* wavelength (micrometers) needs to be introduced in order to change the relative phases of the microwave outputs by the same amount as the optical phases are changed. Changes in optical path lengths of micrometer dimensions are much more compatible with available electro-optic and integrated optical techniques. A demonstration of this approach employing acousto-optic Bragg cells for frequency difference and phase shifting control by beam steering has been reported [8]. That configuration includes an optical means of "computing" the phase shift appropriate to each channel. However, achievable microwave frequencies are limited to less than 3 GHz in that Bragg cell experiment because of limits on Bragg cell frequency shifting.

Optical phase shifting may be achieved either by mechanical mirror movement [1] or by optoelectronic means, as illustrated in Fig. 1. The semiconductor waveguide has a doping (NIPI) superlattice included in it [5], [15]. The superlattice has contacts selectively accessing the alternating p-doped and n-doped layers. The optical properties of the superlattice, and the waveguide containing it, can be modulated by either electrical or optical injection means. Phase modulation in excess of 5π and power amplitude modulation at the detector of more than 20 dB have been achieved with a 1-mm-long waveguide [5]. Typical data are

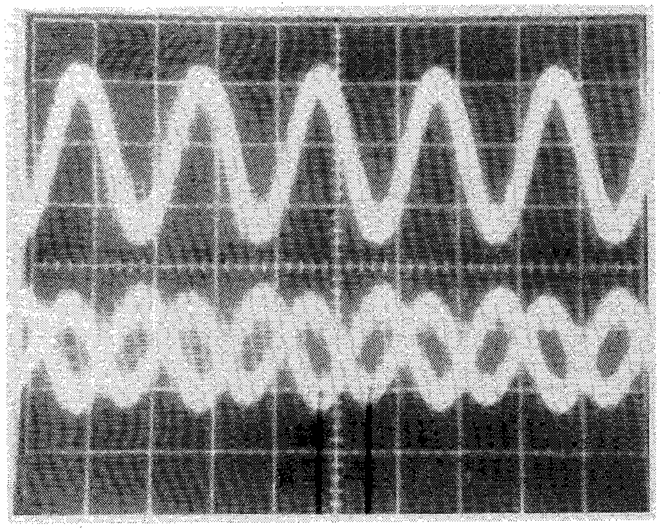

Fig. 4. Two detector outputs, with lower trace showing superimposed phase shifted and unshifted signals through superlattice semiconductor waveguide, 20 ns/div.

shown in Fig. 4. The two traces in the lower channel show both the phase-shifted and unshifted signals incident on the second detector relative to the unshifted signal incident on the first detector. For these data, the phase shift was induced optically by incident argon laser light. A detailed discussion of these superlattice results is provided elsewhere [5].

The optoelectronic approach demonstrated in our work can provide microwave frequency, phase, and amplitude control for many parallel channels in an integrated optical format almost independent of the microwave frequency of interest. This heterodyne approach should also eventually provide microwave frequency and phase hopping on a nanosecond time scale, and has tremendous frequency diversity, as illustrated in Fig. 2.

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Distortion Characteristics of Optical Directional Coupler Modulators

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***Abstract* —Waveguide electro-optic modulators are of much interest for analog optical transmission. Here, a theoretical analysis of the nonlinearities of the intensity modulation response of the optical directional coupler as a function of bias point for the case of phase-mismatch modulation is made and the results are compared with those of interferometric modulators. The interferometric, standard 2×2 directional coupler and the 1×2 y-fed directional coupler modulators are shown to exhibit very similar intermodulation distortion effects. At 4% optical modulation depth, the third-order intermodulation products are −74 dB, −72 dB, and −73.6 dB, respectively, below the carrier level.**

I. Introduction

Electro-optic modulators are intrinsically capable of very high modulation speed and low switching voltage. The optical modulation characteristics of these modulators, i.e., optical intensity output versus applied voltage, are both analog and nonlinear. When used as modulators and switches for digital fiber-optic transmission systems, the nature of the nonlinearity can be used to advantage [1], [2]. However, there is increasing interest in linear analog systems applications. On-ground transmission of satellite communication and radar signals [3]–[5], subcarrier multiplexing techniques [6], laboratory and test instrumentation [7], and sensors are examples where analog modulation with multigigahertz bandwidths would be required. Waveguide electro-optic modulators are also of much interest for multichannel CATV applications because of their potential advantages. These include nearly frequency-independent distortion characteristics, negligible second harmonic distortion if suitably biased, and the ability to increase the output optical power level independent of the modulation depth. The last of these provides the possibility of a larger signal-to-noise ratio and makes it possible to broadcast to several receivers. Additionally, these modulators can exhibit a virtually chirp-free optical spectrum [8] and thereby avoid distortions that might otherwise arise from Fabry–Perot effects created by weak optical reflections within the system.

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