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OPTICAL TECHNIQUES FOR MICROWAVE GENERATION, TRANSMISSION, AND CONTROL

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ABSTRACT

Techniques for optical generation of microwave signals to 35 GHz, including direct laser diode modulation, FM sideband injection locking of laser diodes, and offset frequency phase locking of solid state lasers will be reviewed. Optical methods for controlling microwave devices, including phased array radar and oscillators will be described together with recent advances in optical transmission of microwave signals.

INTRODUCTION

The use of light for generation and transmission of microwave signals, signal processing, control of oscillators and radar has been recently under active investigation and is discussed below.

Techniques for superimposing a microwave signal on an optical carrier are of great practical interest due to the inherently low transmission loss coefficients of optical fibers. In the simplest approach, microwave signals can be impressed on the optical carrier through the direct current modulation of a laser diode[1,2] or with a guided-wave electro-optic modulator.[3] Because of the broadband characteristics of direct laser modulation, this method is well suited not only for transmission of single frequency microwave tones but also for more complex microwave signals with large information content. It is limited however by the maximum laser modulation frequency and by a microwave noise floor caused by the laser intensity noise. These limitations can be circumvented by heterodyning of two frequency-offset low-noise lasers in a fast photodetector, a technique suitable for generation and transmission of narrowband microwave signals. This method, although simple in implementation, generates a microwave signal with a large spectral width due to the laser linewidth. Low phase noise, narrowband heterodyne signals can be achieved by establishing phase coherence between the two lasers through the use of optical injection locking, as was used in the FM sideband injection-locked laser diode microwave generation[4] or by frequency offset electronic phase locking.[5-7]

Optical control of microwave devices includes injection locking and phase control of microwave oscillators using an optically injected microwave signal[8-11] and optical generation of microwave signals for beam control in a phased array radar.[12] In microwave signal processing, optical methods have been used to create fiber microwave delay lines[13] with time-bandwidth products much larger than possible with other techniques, microwave frequency filters[14] and discriminators,[15] and radar signal processing such as a moving target indicator.[16]

Although not directly addressed here, development of digital lightwave communications to multigigabit rates, including demonstrations of transmission of 11 Gb/s[17] and 2.7×10^7 time-bandwidth products,[18] could have significant impact on microwave applications.

MICROWAVE GENERATION

Direct laser diode modulation, because of its simplicity and wide bandwidth capability, is the most attractive method for generation of a microwave signal at a remote photodetector. For short links the maximum microwave frequency and signal to noise (S/N) are limited by the laser diode characteristics. Although exceeded in experimental devices, the typical modulation bandwidth of a high-speed 1300-nm laser diode[19] is ~15 GHz and represents the practical upper frequency limit. The S/N_{out}, equivalent input noise (EIN), laser relative intensity noise (RIN), and link noise figure F are all related by

$$(S/N)_{out} = \frac{S_{in}}{kT\cdot F} \quad (1)$$

$$F = \frac{EIN}{L\cdot kT} = \frac{RIN\cdot(P/\eta)^2\cdot Z_{LD}}{L\cdot kT} \quad (2)$$

where S_{in} and S_{out} are the available signal power levels, B is the detection bandwidth, L is the link electrical losses, kT is -174 dBm/Hz, P is the average laser output power, Z_{LD} is the laser input impedance, and η is the laser dc conversion efficiency. The performance then depends on the laser intrinsic noise (RIN), which has a resonance just below the 3-dB modulation bandwidth. Typical $(S/N)_{out}$ is 50 dB at 18 GHz for 0 dBm drive power and a 1-MHz detection bandwidth.[20] An undesirable feature of direct modulation is the presence of harmonics due to the nonlinearities in the laser power vs. current response. In the frequency range of 5 to 15 GHz, the second harmonic to fundamental microwave power ratio is typically -10 dB but can be as little as -5 dB for reasonable (30%) modulation depth and laser bias ($3 \times I_{th}$). Another disadvantage is the non-flat frequency response, which either has to be compensated for or, in certain applications such as frequency response measurements of opto-electronic components, must be calibrated out.

Mixing of two free-running lasers can be used to generate microwave signals to a maximum frequency limited by photodetector bandwidth which has been demonstrated to be at least 100 GHz.[21] The technique is inherently suited for generating narrowband microwave signals with little power variation as a function of frequency and negligible harmonic content. In addition, the S/N can be higher than with direct modulation since lasers can be selected with low 3-dB bandwidths so that the generated microwave signal is beyond the rolloff point of the RIN thereby making its effect negligible when compared with other noise sources. Recently, the technique was implemented with laser diodes,[22] and with laser diode pumped Nd:YAG ring lasers[23,24] for measuring of the frequency response of photodiodes and electro-optic phase and amplitude modulators. A drawback of this technique is the large spectral width of the microwave signal which is caused by low frequency phase noise in the lasers. The phase noise is upconverted to the microwave frequency by the mixing process causing phase noise in the generated signal, with the resultant microwave linewidth equal to approximately two times the optical linewidth of the laser. Beat signal linewidths are in the 5-50 MHz range for solitary laser diodes and less than 10 kHz for Nd:YAG ring lasers.

The linewidth of the microwave signal generated by mixing of emissions from two frequency-offset lasers can be drastically reduced by eliminating the relative optical phase fluctuations between them, thereby making them phase coherent. One method for accomplishing this is FM sideband optical injection locking of laser diodes,[4] where a master laser is directly current modulated at a subharmonic of the microwave frequency to be generated to create sidebands in the laser optical spectrum, as shown in Fig 1. Two of these sidebands can then be selectively amplified by two slave laser diodes which are injection locked by the master laser. As a result, the two slave lasers are phase coherent with the master laser and each other, while their frequency separation equals an integer multiple of the master laser modulation frequency. In a modification of this method,[25] the two master laser sidebands are amplified by a single slave laser with a longitudinal mode spacing of 35 GHz, chosen to equal the frequency separation of the +3 and -3 sidebands of the master laser modulated at 5.8 GHz. The 35 GHz microwave signal generated exhibited a resolution-bandwidth-limited linewidth of 10 Hz.

A more practical method of achieving phase coherence between two frequency offset lasers is through electronic phase locking, where the phase of one of the lasers is actively controlled. The method can be implemented with lasers which have narrow linewidths and therefore exhibit phase fluctuations only at low frequencies which can be easily handled by conventional electronic feedback loops. Frequency offset phase-locking has been implemented with external cavity laser diodes[5] and laser diode pumped Nd:YAG ring lasers.[6,7] In the latter case the two lasers are mixed by superimposing their outputs in a fast photodetector, as shown in Fig. 2. The phase of the beat signal is then

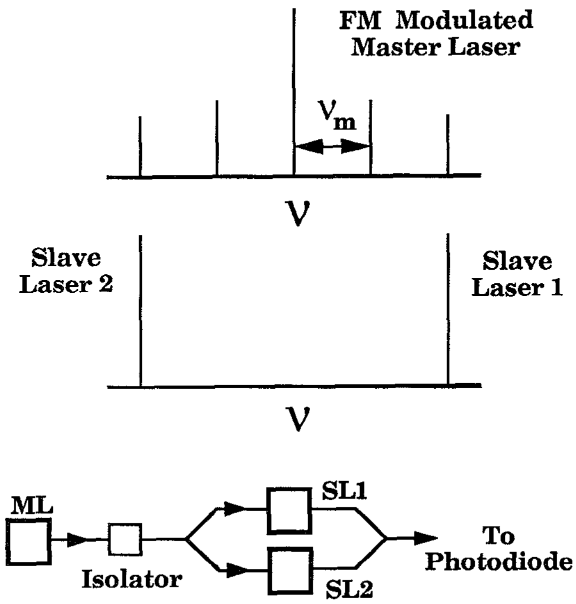

Figure 1. FM Sideband Optical Injection Locking of Laser Diodes

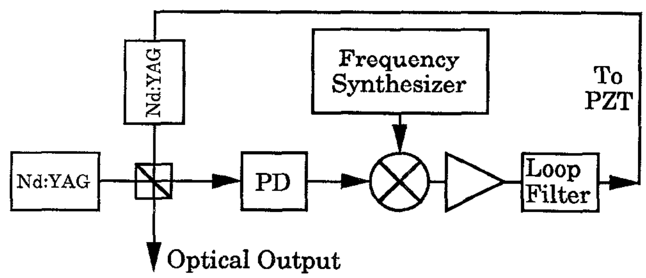

Figure 2. Offset Phase Locking Nd:YAG Lasers

compared with the microwave phase of a synthesized oscillator using a double balanced mixer. The mixer output voltage, which is proportional to the phase difference between the beat and reference signals, constitutes an error signal which is fed back to one of the lasers to form a PLL. This voltage controls the laser frequency and phase through a piezoelectric element by altering the laser cavity length and hence the oscillating frequency. With appropriate feedback loop gain and filtering, the relative phase fluctuations between the two lasers are reduced and the beat signal is phase locked to the microwave reference. The system shown in Fig. 2 was used to generate microwave signals from .05-40 GHz, and with proper microwave components can be extended to 100 GHz. The linewidth of a 30 GHz beat signal was less than 1 milliHertz, where the effects of frequency drift of the frequency synthesizer have been removed.[6]

OPTICAL CONTROL OF MICROWAVE DEVICES

One of the most active research areas in the field of optical control of microwave devices has been optical injection locking of microwave oscillators. Direct injection of the optical signal into the active component[8-11] and the use of a photodetector to downconvert the microwave signal from the optical carrier[26] before injection have been explored. Some of the early work included IMPATT oscillators and subharmonic locking[8] while more recently FET oscillators and fundamental frequency injection locking was used.[10,11] Optical injection locking of a 7.2 GHz FET oscillator is illustrated in Fig. 3, where

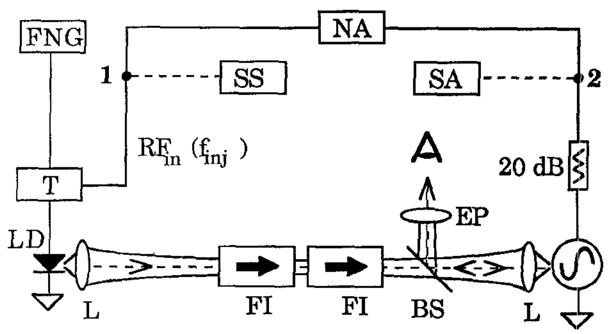

Figure 3. Optical Injection Locking at 7.2 GHz with Phase Control

both the amplitude and the relative phase of the oscillator output at the injected frequency were measured on a network analyzer.[11] Typically, with 1.0 mW of incident optical power, a locking bandwidth of 3.0 MHz was measured for an oscillator output of 3 dBm. Approximately 180 degrees of phase deviation could be achieved between the injected and the output signals by tuning the injected frequency or by (optically) tuning the oscillator free running frequency by changing the average power level of the incident optical signal. Optical injection locking of microwave oscillators can be used for achieving phase coherence between remote oscillators as in phased array radar and in optical fiber communication links.[27]

Because of the relative ease of injecting a microwave signal on an optical carrier into the active device, optical injection is also an attractive method for downconversion of high frequency microwave signals impressed on optical carriers.[28-30] It has been shown that an FET oscillator can simultaneously perform the functions of demodulation (photodetection) of the microwave signal from the optical carrier, generation of a local oscillator frequency and harmonics through self-oscillation and transistor nonlinearities, and downconversion of the demodulated microwave signal to a lower frequency by nonlinear mixing of the demodulated signal with the local oscillator signal and its harmonics. With a 27.5 GHz FET oscillator, this technique was used to detect and downconvert microwave signals up to 89 GHz to a 6.5 GHz IF band.[30]

An optical method based on coherent mixing has also been demonstrated to be useful for phased array radar control.[12] The technique, shown in Fig. 4 is based on generating a moving sinusoidal optical intensity pattern generated by interference between two coherent, frequency offset optical beams which interfere at a small angle. The pattern is spatially sampled with a periodic fiber array, and the the sinusoidal intensity vs. time variation in each fiber is then converted into a microwave signal by a photodetector. As a result, each detector generates a microwave signal which is phase shifted from its neighbor by a constant amount depends on the period of the sinusoidal interference pattern, and can therefore serve as the microwave signal source for a corresponding phased array antenna element. The phase vs. position gradient across the fiber array was controlled in real time by changing the interference angle between the two beams with an acoustooptic deflector. Using a linear emitter array of 7 elements and a microwave frequency of 3.2 GHz the generated antenna beam pattern, shown in Fig. 4, exhibited excellent agreement with a pattern calculated for a uniformly illuminated antenna array.

SUMMARY

We have reviewed the uses of light for microwave signal generation and processing. Optical techniques offer both improvements and new capabilities for microwave applications.

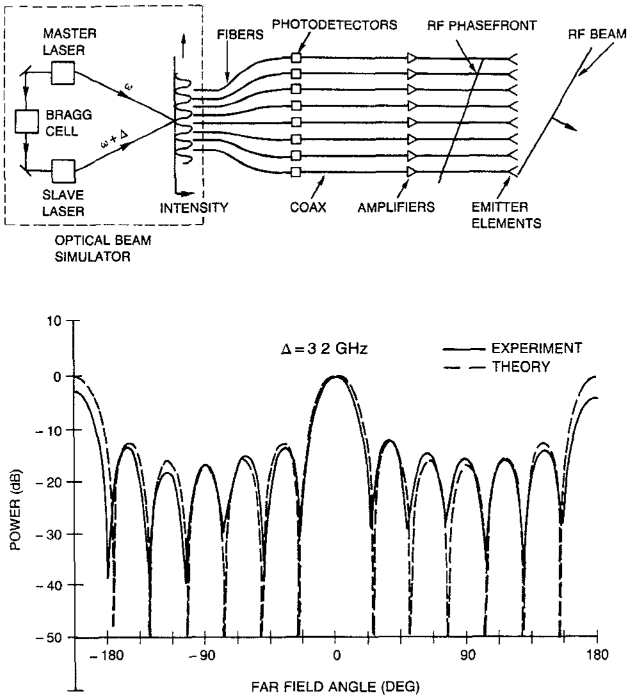

Figure 4. Seven-Element Phased Array Optical Feed Configuration and Antenna Patterns

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