Multiple RF Carrier Distribution in a Hybrid Radio/Fiber System Employing a Self-Pulsating Laser Diode Transmitter

A. Kaszubowska, L. P. Barry, and P. Anandarajah

Abstract—**A self-pulsating laser diode is used to generate a multicarrier microwave optical signal for use in a hybrid radio/fiber system. The self-pulsation frequency of the laser is controlled by external light injection, and can be varied between 14–24 GHz. The hybrid radio/fiber system, employing the self-pulsation laser, is used to distribute two 155–Mb/s data signals on two radio frequency (RF) carriers (at 18.5 and 18.9 GHz). Experimental results show the overall system performance for both RF channels, and demonstrate that the performance is improved by around 17 dB compared with the case when the laser is used without external injection, and thus, does not self-pulsate.**

Index Terms—**External light injection, microwave photonics, optical communications, optical systems, self-pulsation, semiconductor laser diode.**

I. Introduction

HIGH CAPACITY mobile networks of the future will probably use high-frequency microwave signals as the access medium (15–60 GHz), as this offers a large bandwidth for data transfer. These high-capacity microwave systems are likely to employ an architecture in which signals are generated at a central location and then distributed to remote base stations using optical fiber, before being transmitted over small areas using microwave antennas [1], [2]. Such an architecture should prove to be highly cost efficient, since it allows sharing the transmission and processing equipment (remotely located in the central control station) between many base stations. It is also expected that these broad-band mobile networks will divide the available transmission bandwidth into a number of RF channels for broadcasting data "over the air." This use of multiple carrier distribution is normally required in high-capacity multipath environments in order to overcome multipath fading effects.

On the transmission side of a radio-over-fiber distribution network it is necessary to generate the microwave optical data signal using semiconductor laser diodes. The simplest technique available to generate optical microwave signals involves direct modulation of the laser with the microwave data carriers. However, the limited bandwidth of laser diodes means that we are normally unable to use high frequency RF carriers ($>$10 GHz). One possible solution is to use active mode locking of a laser diode cleaved to an appropriate length such that resonant enhancement of the microwave signals may be achieved with direct modulation [3]. However, this technique requires specially designed devices that only operate at specific frequencies. Another technique to overcome the limited bandwidth of laser diodes is to employ external optical injection into the laser, as this can greatly increase the intrinsic modulation bandwidth of the diode [4], [5]. In addition, at high injection levels, the laser can start to self-pulsate at frequencies that are suitable for RF transmission, thus making the device useful for the generation of microwave optical signals in hybrid radio/fiber networks [6], [7]. In a previous letter, we showed that the performance of a single channel radio-over-fiber system can be enhanced by using this external injection technique [8]. In this letter, we characterize the self-pulsation in the laser under external injection locking conditions, and demonstrate how the injection-locked commercial laser may be employed in a hybrid radio/fiber system for the distribution of multiple-carrier RF data signals.

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II. Self-Pulsating Laser Characteristics

The laser diode used for the experiments is a standard multiple-quantum-well distributed-feedback (DFB) device from NEL. The laser has a threshold current of 26 mA, and an intrinsic modulation bandwidth of around 8 GHz. By injecting light from a wavelength tunable external cavity laser, at the same wavelength as the DFB emission wavelength, we significantly alter the modulation response of the device, and can achieve excellent response at frequencies from 14 to 25 GHz. The enhanced response at these frequencies is caused by the external injection inducing instability in the laser diode. The instability, in turn, results in the output power from the laser undergoing strong oscillations due to beating between the optical field components in the laser cavity [6]. Fig. 1 displays the optical spectrum from the laser when it is biased at 60 mA and the externally injected power from the external cavity laser is 5 mW. We can clearly see the modulation on the spectrum at a frequency of around 20 GHz. To further investigate the oscillation from the laser, the optical output from the laser under external injection was detected with a 50–GHz photodiode and displayed on a 50-GHz oscilloscope. Triggering was achieved by splitting the electrical signal after the detector in two, and using one of the outputs as the trigger. Fig. 1(b) displays the detected signal. We can clearly see the oscillation at a frequency of around 20 GHz, and also the significant level of noise and jitter on the signal. This noise and jitter on the oscillation from the laser is also evident in the detected electrical spectrum [Fig. 1(c)], and the broad linewidth is caused by the jitter between the DFB laser diode and the tunable cavity

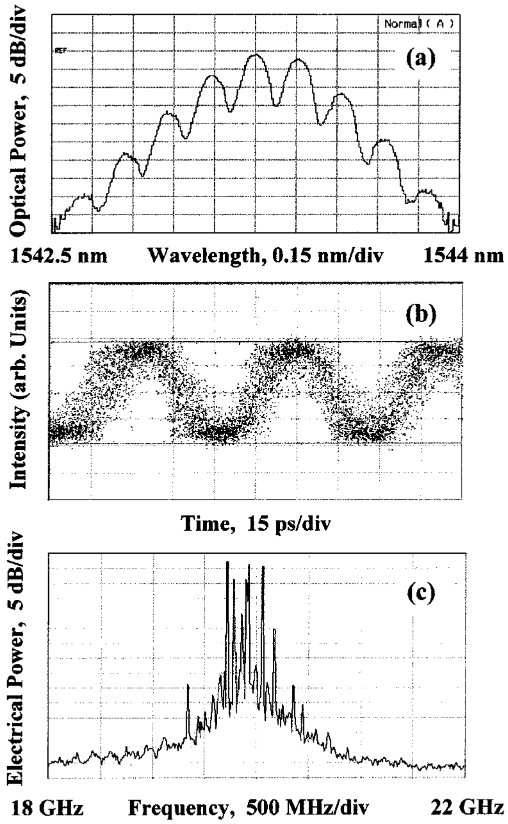

Fig. 1. (a) Optical spectrum. (b) Detected output power oscillation. (c) Electrical power spectrum of DFB laser biased at 60 mA with external injection level of 5 mW.

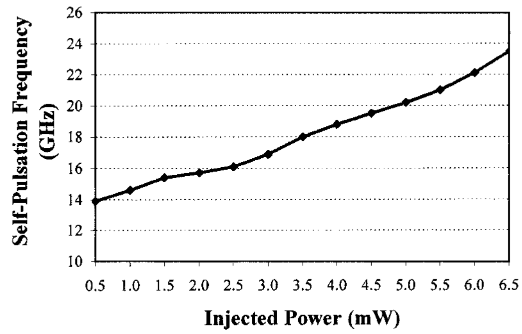

Fig. 2. Self-pulsation frequency from externally injected DFB laser as a function of injected power level.

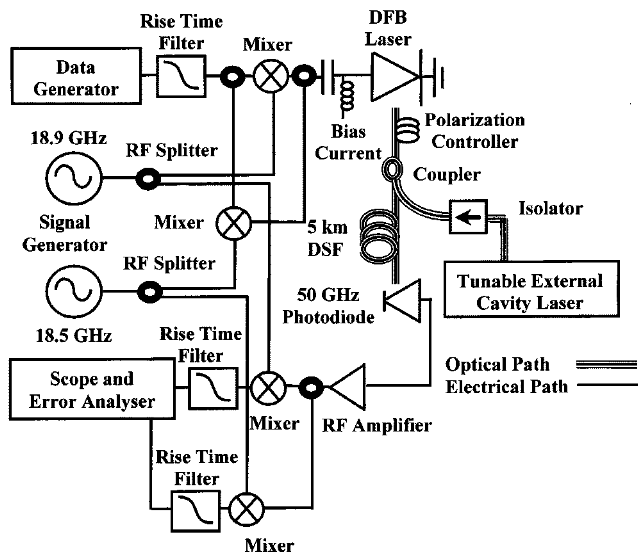

Fig. 3. Experimental set up for multicarrier hybrid radio/fiber system using self-pulsating laser diode.

laser. The frequency of the oscillation from the injection-locked laser depends on the strength of the injected optical signal [6], and Fig. 2 displays how the oscillation frequency varies as a function of the injected power level. In addition, by measuring the peak-to-peak voltage of the oscillation on the oscilloscope, we have been able to determine that the optical output from the laser is 100% modulated.

III. Multicarrier Radio-Over-Fiber Setup

As we have stated in the introduction, future broad-band RF networks will require multicarrier microwave systems to overcome multipath fading. It will be necessary for optically fed microwave systems employing self-pulsing laser diodes to be capable of handling multiple RF carrier data signals. To demonstrate this, we have used the experimental arrangement described in Fig. 3. A 155-Mb/s nonreturn-to-zero (NRZ) data stream from an Anritsu pattern generator is initially passed through a 117-MHz low-pass filter to minimize the bandwidth of the electrical data signal, and then split in an RF coupler. The two signals are subsequently propagated through cables with a length difference of 1.5 m in order to ensure that there is no correlation between the two data channels. One of the two data streams is then mixed with an 18.5-GHz RF carrier, and the second data stream is mixed with an 18.9-GHz RF carrier, resulting in two binary phase-shift keyed (BPSK) data signals. The RF data signals are then combined together, and the resulting multicarrier microwave data signal is used to directly modulate the DFB laser diode described above. The data signal comprising two RF carriers can be applied either to the free-running laser or to the laser diode into which light is injected from the tunable external cavity laser. In both cases, the RF data signal is combined with a dc bias current of 60 mA. The resulting optical microwave data signal from the laser is then passed through 5 km of dispersion-shifted fiber before being detected with a 50-GHz p-i-n photodiode. In a complete radio/fiber system, the detector output would be transmitted through an RF antenna to the mobile stations, however, in our experiment we have concentrated on the optical part of the system. Hence, the down conversion of the two RF carrier data signals takes place after the photodiode. To recover the two data channels simultaneously, the detected signal is split in two. One of the signals is then down converted by mixing it with the 18.5-GHz local oscillator, and the second signal is down converted by mixing it with the 18.9-GHz local oscillator. The two down-converted signals are subsequently passed through low-pass filters to ensure that only the required baseband signal is examined using the 50-GHz oscilloscope and error analyzer. Using the oscilloscope, we are able to characterize the received eye diagrams of the two 155-Mb/s data signals, and with the Anritsu error analyzer we can determine the bit-error rate (BER) of the received signals.

Fig. 4(a) displays the received eye diagrams (displayed simultaneously on the oscilloscope) of the two down-converted

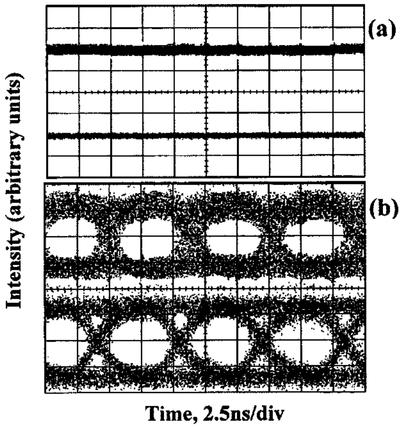

Fig. 4. Received eye diagrams of the two 155-Mb/s data signals from the optically fed microwave system using (a) free running laser diode and (b) laser diode with the external injection level of 4 mW. Received optical power (before photodiode) was −9 dBm in both cases.

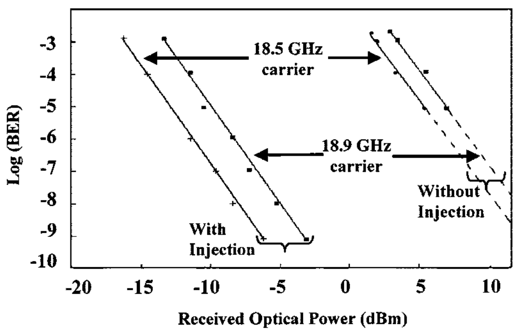

Fig. 5. BER versus received optical power for the two RF data channels using directly modulated laser with and without external injection.

155-Mb/s data signals after propagation through the optical microwave link using the DFB laser with no external light injection. The detected average optical power is −9 dBm. As we can see, because the response of the laser is so poor at frequencies around 18 GHz, the received eye diagrams are completely closed. We then proceeded to inject light into the DFB laser from the wavelength tunable external cavity laser at the same wavelength as the DFB emission wavelength. The injection level is set to around 4 mW, as this is the power level that optimizes the modulation response of the laser at the frequencies of the microwave data signal. Fig. 4(b) displays the simultaneously received eye diagrams with a detected optical power of −9 dBm. The eyes are clearly open for both data channels, demonstrating good system performance. By varying the detected optical power level using an optical attenuator, and measuring the BER of the received signals, we can plot system performance against received optical power, both with and without the external injection. Fig. 5 shows that the external injection improves the overall performance of the system by around 17 dB for each RF data channel. The difference in performance for the two RF data channels is mainly due to the different synthesizers used for the 18.5 and 18.9-GHz carriers.

The RF powers in the two data signals applied to the laser are around −12 dBm. At these low power levels, the laser does not tend to completely lock to either of the data signals applied. However, the small-signal modulation response of the self-pulsating laser does show greatly enhanced performance over a significant bandwidth [similar to that shown in Fig. 1(c)], and it is this enhanced response that improves the performance of the multicarrier system. On the issue of crosstalk, interchannel crosstalk between the data signals is negligible, as the 400-MHz channel spacing is sufficiently larger than the 117-MHz bandwidth of the data signals. In addition, crosstalk due to fiber nonlinearity, which is predominantly caused by four-wave-mixing in subcarrier multiplexing (SCM) systems with low data-rate per channel and narrow channel spacing [9], can be neglected thanks to the small number of channels and low optical power launched in the fiber (−4 dBm). However, as the channel spacing is further reduced to improve spectral efficiency, and the number of channels and launched power is further increased, it will be important to investigate degradations in system performance due to crosstalk in more detail.

IV. Conclusion

We have demonstrated the use of a self-pulsating laser diode (achieved using external injection into a commercial DFB laser) for the distribution of multicarrier RF data signals in a hybrid radio/fiber communication system. As the frequency of the self-pulsation is determined by the external injection level, we can vary the set up to operate in different frequency bands. Our results show that we can successfully modulate the self-pulsating laser with two RF data signals simultaneously, giving us a 17-dB improvement in system performance, for each RF data channel, above what would be achieved using the laser diode without external light injection. In future work, we intend to investigate how intermodulation distortion will effect the performance of a multicarrier hybrid radio/fiber system using self-pulsating laser transmitters, however, our initial work has demonstrated that such a scheme may be feasible for the development of broad-band microwave communication systems.

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