High-performance, externally modulated analog fiber-optic links

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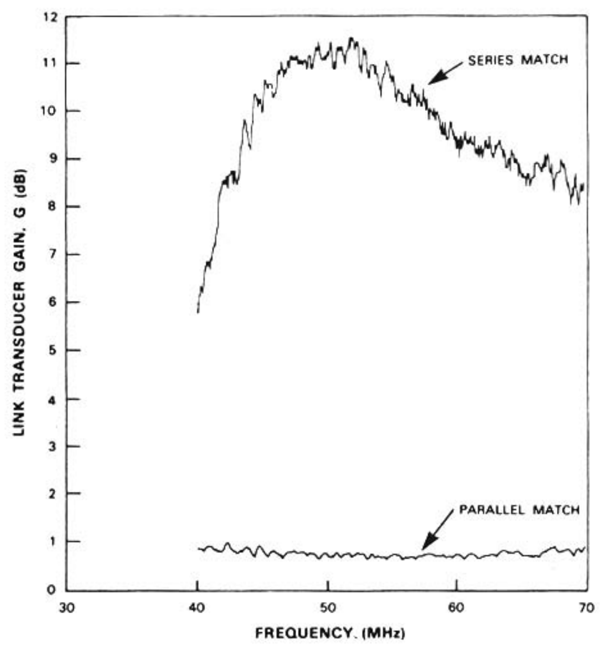
Fiber-optic links are finding an increasing number of uses in analog RF systems. In most applications, information is impressed on the optical carrier by modulating the current of a semiconductor diode laser, a process referred to as direct modulation. Alternatively, the laser is operated continuously, and an external modulator is coupled to the laser output. Some advantages of the latter approach, which has been known for some time, [1–3] are now being recognized.

We have demonstrated[4] net small-signal RF gain in a link consisting of laser, external modulator, and pin photodiode, but no RF amplifier. This gain may be one advantage of external modulation, but an effect of the gain may have even more significance: the equivalent input noise of this type of externally modulated link is less than that of a directly modulated link. This, in turn, permits a larger intermodulation-free (IM-free) dynamic range in an externally modulated link, notwithstanding an indication[5] that, at the same optical modulation depth, the third-order distortion of an external modulator is greater than that of a diode laser.

To understand these improvements, we formulated simple small-signal models of a laser, external modulator, and pin photodiode, and cascaded them to form an externally modulated link. The resulting link model[6] explicated the effect of device parameters, such as laser power and modulator sensitivity, on such link parameters as insertion loss or gain, noise, and IM-free dynamic range. A key finding was that RF gain is proportional to the square of the optical bias power and to modulator sensitivity. Thus, with sufficiently high laser power and modulator sensitivity, RF loss is overcome, resulting in a net small-signal gain. If we assume that the laser's relative intensity noise (RIN) is negligible at high optical power levels, the main sources of noise are the passive input matching circuit (thermal noise) and the photodetector (shot noise). Shot noise increases linearly with optical bias power. Since link gain varies proportionally with the square of the optical bias power, the contribution of shot noise to link input noise can, in principle, be suppressed to arbitrarily low levels. Thus, the link noise figure asymptotically approaches the thermal noise limit of 3 dB, which corresponds to the value of the thermal noise.

To verify these results, we constructed an externally modulated fiber-optic link and measured its performance.[4] The external modulator is an integrated-optic Mach-Zehnder interferometric modulator implemented in LiNbO_3. The diode-laser-pumped Nd:YAG laser has a fiber-coupled optical power of 55 mW at 1.32 μm (a secondary emission line), so its power is substantially higher than the 1 mW typical of present diode-laser-based links, and its RIN for frequencies >1 MHz is significantly lower. The RF output of the InGaAs pin photodiode feeds a 50-Ω resistor.

Measurement of link insertion loss versus frequency demonstrates a link transducer gain of ~1 dB with input to the modulator terminated by a 50-Ω resistor (see figure). This link has a low-pass 3 dB bandwidth of ~150



Frequency responses of the optical analog link with the input to the modulator terminated by a resistor (parallel match) and with a tuned circuit on the modulator (series match).

MHz. However, if the resistor is replaced with a tuned impedance-matching circuit,[7] the gain increases to ~11 dB with a center frequency of ~60 MHz and a 3 dB bandwidth of ~20 MHz. With the tuned circuit on the modulator, the link noise figure is 6 dB and the IM-free dynamic range is 111 dB within a 1 Hz bandwidth. The range from maximum input signal to the noise floor is 155 dB/Hz. With some sacrifice in sensitivity, a higher IM-free dynamic range can be obtained by the dual-polarization approach described by Johnson and Roussell.[8] These measured values agree well with theoretically calculated values over the entire 150 dB input power range.

Extrapolation to higher center frequencies is straightforward. Since the modulator can be modeled as a capacitor, the maximum possible response decreases inversely with the square of the increase in frequency. As the frequency increases, the gain decreases and the noise increases, but the dynamic range remains nearly unchanged. Thus, for low-to-moderate frequencies and moderate-to-high optical bias powers, the externally modulated link is expected to provide lower insertion loss or actual insertion gain, a larger IM-free dynamic range, and less noise than a directly modulated link.[9]

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Dynamic optical interconnects

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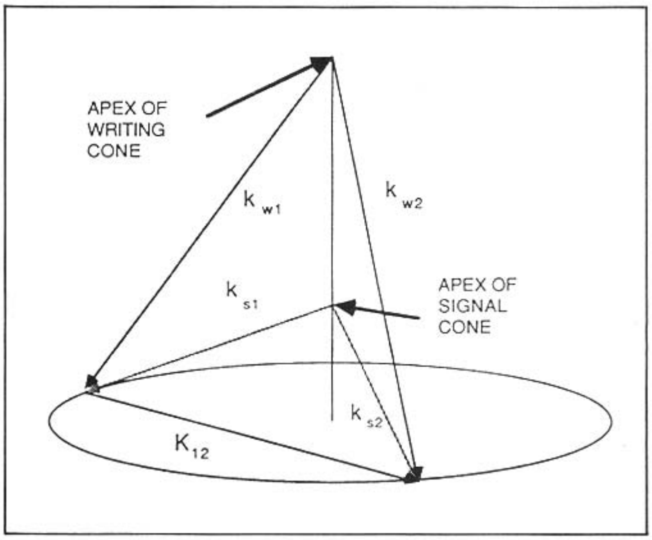
Dynamic optical interconnects are reconfigurable routing networks that can interconnect high bandwidth optical data paths. The optical crossbar is an example of an attractive architecture that can be implemented using photorefractives. Once the routing network has been established, optical inputs are reflected, refracted, or diffracted passively to their respective outputs. Upon termination of the task, the network can be reconfigured and adapted to new routing requirements. The major advantage of this approach is the high optical transmission bandwidth (GHz), although the reconfiguration time may be slow (on the order of msecs or μsecs).

Architectures involving photorefractive crystals have been implemented for this purpose, but several limitations need to be overcome to fully exploit the potential advantages of these systems. As is well known, readout of holographic gratings in photorefractives is destructive, unless fixing procedures are applied or the wavelength of the readout light is used in a regime where the photorefractive crystal is not sensitive. In this case, however, the Bragg condition still needs to be satisfied to achieve high diffraction efficiency. We have recently devised a new architecture to achieve prolonged readout.[1]

In this approach, the interconnect gratings are written by beams of wavelength λ_w and readout by using signal beams of longer wavelength λ_s. Unlike previously proposed networks, the writing wavelength does not have to be tunable. The Bragg condition is still maintained by locating the recording and readout beams on a conical geometry, as shown in the figure. The writing k-vectors K_{wi} lie on the surface of a cone and emanate from the cone apex. The signal k-vectors K_{si} (either inputs or outputs) lie on a second cone, which has the same base, but whose height is scaled by the ratio of the wavelengths. We estimate that in SBN, approximately 5,000 interconnections could be established and used for prolonged time periods (hours) without significant erasure.



K-vector diagram for conical geometry.