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Equalization in Coherent Lightwave Systems Using Microwave Waveguides

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Abstract—**The maximum bit rate-distance product in recent single-frequency laser direct-detection lightwave system experiments has been limited by dispersion. Here we consider an equalization technique, appropriate for coherent lightwave systems, that uses a microwave waveguide for overcoming the delay dispersion problem. Results show that small low-loss waveguides can be used to greatly reduce dispersion. For example, an 8-GHz bandwidth signal transmitted over 68 km of fiber can be equalized by a waveguide with a cross section of 6 × 3 mm and a length of only 17 cm. With the waveguide equalizer, the dispersion-limited maximum bit rate-distance product for a standard fiber system can be increased to that of a dispersion-shifted fiber system at 1.55 μm, e.g., a 16-fold increase in maximum bit rate for 100-km transmission distances.**

I. INTRODUCTION

THE MAXIMUM bit rate-distance product in recent single-frequency laser direct-detection lightwave system experiments has been limited by dispersion. Here we consider an equalization technique, appropriate for coherent lightwave systems, that uses a microwave waveguide for overcoming the delay dispersion problem.

II. EQUALIZATION

In a recent experiment [1], 8 Gbit/s were transmitted over 68 km using a single-frequency laser at 1.55 μm with a single-mode fiber and *direct detection*. The distance is limited to 68 km because of chromatic dispersion in the fiber, the major portion of which is the linear dispersion of 17 ps/km/nm. In coherent systems, distance limitations due to chromatic dispersion can be even lower [2]; however, microwave devices with dispersion can be used at the receiver to equalize the chromatic dispersion. This was shown in [3], where a microstrip line was used. In this paper we consider another device to equalize chromatic dispersion, a microwave waveguide. The advantages of the waveguide include lower radiation (i.e., interference) from the device into other parts of the receiver and lower signal attenuation, while the disadvantages include a higher IF frequency in the waveguide and possibly more expensive construction than a microstrip line. The magnitude of the slope of the dispersion per unit length of these two devices is roughly comparable; however, the sign of the slope is opposite. Thus, to compensate for dispersion at 1.55 μm in a standard fiber (with a dispersion minimum at 1.3 μm) the LO at the receiver must be higher in frequency than the received signal when a microwave waveguide is used and lower in frequency when a microstrip line is used [3]. Note that dispersion with the opposite slope can be equalized by reversing the relationship of the LO and received signal frequencies.

Fig. 1 shows the coherent system with a waveguide equalizer. As shown in this figure, the received optical signal is first mixed with an optical signal, offset from the received signal by an IF frequency in the microwave range (e.g., 40 GHz). The IF microwave signal propagates through a waveguide to equalize the linear portion of the dispersion, and then the data bits are detected. To equalize the received signal, 1) the LO must track the received signal to within about 100 MHz (so that timing delay error due to frequency offset is only a few percent), 2) the mixer must be approximately linear, and 3) the waveguide must be properly sized. Assuming the first two conditions can be met, below we consider the third issue.

Consider a rectangular waveguide of cross section $a \times b$, using the TE_{10} mode [4]. Such a waveguide has a cutoff frequency of

$$f_c = \frac{c}{2a} \tag{1}$$

where c is the speed of light (3×10^8 m/s), and, with $b = a/2$, is single mode up to $2f_c$. Now, to compensate for the dispersion in the fiber, we wish to choose f_c, and a bandwidth B in the waveguide such that the time delay is approximately linear across the bandwidth. The time delay is most closely linear near $2f_c$; however, to allow for a safety margin, let the highest frequency be $1.86f_c$. For frequency $f > f_c$, the group velocity is given by

$$v_g = c\sqrt{1 - (f_c/f)^2} \tag{2}$$

and, thus, the time delay across a fraction α of the bandwidth B ($1.86f_c - B < f < 1.86f_c$) is given by

$$\Delta T(\alpha) = \frac{L_1}{c}\left(1.186 - \frac{1}{\sqrt{1 - \left(\dfrac{1}{1.86 - \alpha B/f_c}\right)^2}}\right) \tag{3}$$

where L_1 is the length of the waveguide and $0 \le \alpha \le 1$. (Note that at frequency f, $\alpha = (1.86f_c - f)/B$.) Fig. 2 shows the normalized time delay versus normalized frequency (α) for various B/f_c. Note that the time delay is

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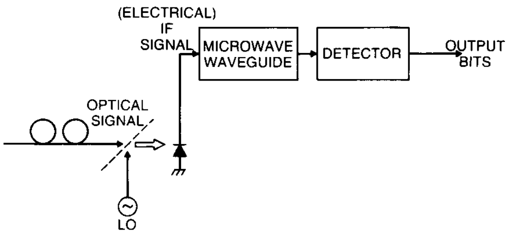

Fig. 1. Receiver with microwave waveguide equalizer.

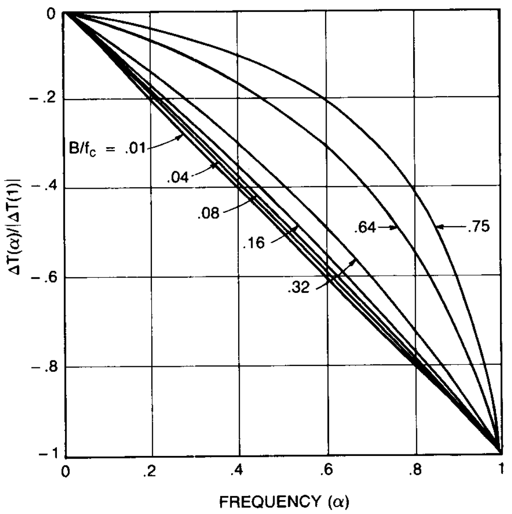

Fig. 2. Normalized delay versus frequency (α) for several B/f_c, where α is the fraction of the bandwidth B, $\alpha = (1.86f_c - f)/B$.

within 10 percent of linear for $B/f_c < 0.32$ (within 5 percent for $B/f_c \leq 0.16$).

Next, consider the length of the waveguide. For a fiber operating at the loss minimum of 1.55 μm, we have [5]

$$\frac{\Delta T}{BL} = 17 \text{ ps/km/nm} \tag{4}$$

or

$$\Delta T = -0.14 \times 10^{-12} BL \quad \text{s} \tag{5}$$

with B in gigahertz and L in kilometers. Thus, from (3) and (5), the length of the waveguide is given by

$$L_1 = \frac{-4.2 \times 10^{-5} BL}{\left[1.186 - \left(1 \Big/ \sqrt{1 - \left(\frac{1}{1.86 - B/f_c}\right)^2}\right)\right]} \text{ m.} \tag{6}$$

Note that for $B/f_c > 0.14$, $L_1 < 10^{-3} BL$ m.

Finally, consider the loss in the waveguide, which for a silver waveguide at $f = 1.86f_c$ is (as derived from [6])

$$\text{attn} = 5.14 \times 10^{-3} f_c^{3/2} L_1 \quad \text{dB} \tag{7}$$

where f_c is in gigahertz.

As an example, consider the case of $B = 8$ GHz, $L = 68$ km. Table I lists the parameters for the waveguide for various f_c. Note that for $f_c = 25$ GHz the waveguide has a cross section of 6×3 mm, length of 17 cm, and an attenuation of about 0.1 dB.

TABLE I
WAVEGUIDES FOR EQUALIZATION WITH B = 8 GHz AND L = 68 KM

f_c (GHz)	B/f_c	a (mm)	L_1 (m)	attn (dB)
200	.04	.75	2.1	30
100	.08	1.5	1.0	5.1
50	.16	3.0	.46	.83
25	.32	6.0	.17	.11
12.5	.64	12.0	.041	.0093

Finally, we note that if the waveguide completely removes the linear portion of the delay, then the delay dispersion in the output signal is primarily due to the quadratic portion of the delay. It is interesting to note that the quadratic portion of the delay in the waveguide has the opposite sign of the quadratic delay in the fiber [7], independent of the relationship of the LO and received signal frequencies. Thus, both the linear and quadratic portion of the delay can be cancelled by the waveguide. However, in systems operated at wavelengths other than the dispersion minimum of the fiber, the quadratic portion of the delay is a very small fraction of the total delay (less than 0.1 percent for a 8 Gbit/s signal at 1.55 μm in a standard fiber). In this case the error in the linearity of the waveguide delay determines receiver performance. Note that if the linear portion of the delay is completely cancelled by the waveguide, then the maximum bit rate-distance product of a standard fiber system using the waveguide equalizer is similar to that of a system with a dispersion-shifted fiber at 1.55 μm [5]. For example, over a distance of 100 km, the waveguide equalizer increases the dispersion-limited maximum bit rate about 16 times (from 6 Gbit/s to 100 Gbit/s).[1]

III. CONCLUSION

We have considered the use of a microwave waveguide as an equalizer for coherent lightwave systems. Results show that small low-loss waveguides can be used to greatly reduce dispersion. Specifically, the dispersion-limited maximum bit rate-distance product for a standard fiber system can be increased to that of a dispersion-shifted fiber system at 1.55 μm, e.g., a 16-fold increase in maximum bit rate for 100-km transmission distances.

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[1] For a standard fiber $B^2L \approx 4000$ (Gbit/s)^2 km and for a dispersion-shifted fiber $B^3L \approx 10^8$ (Gbit/s)^3 km [5].

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