High-T_c Superconductor Waveguides: Theory and Applications

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***Abstract*—In this paper, we study the expected properties of high-T_c superconductor waveguides, postulating the existence of such devices in the future. These devices offer the potential of 100 GHz of bandwidth for transmission over long distances with low attenuation, with the advantage over optical systems of wider dynamic range (providing a virtually unlimited number of taps). We first study the theoretical performance of superconductor waveguides including attenuation, carrier frequency and bandwidth, maximum transmitted power, and dispersion. We then discuss potential applications in local area networks.**

I. Introduction

The discovery of superconductivity in materials above the temperature of liquid nitrogen $T_c > 77$ K [1] and hints of superconductivity above room temperature [2] suggest new possibilities for superconductors in digital electronics and transmission [3], [4]. In particular, transmission of electrical signals with 100 GHz of bandwidth over long distances with low attenuation may be possible. It is thus interesting to consider the potential of superconductor devices: both the theoretical limitations and practical applications.

One potential device for transmission is a millimeter waveguide. Millimeter carrier systems have the advantage over optical systems of much lower carrier frequency, which results in wider dynamic range as shown in subsection II-F (providing a virtually unlimited number of taps or decreasing the need for amplifiers). Standard metal waveguides, however, have extremely high signal attenuation at millimeter frequencies (10^4 dB/km at 200 GHz [5, p. 261]) owing to the resistance of the metal walls, and therefore are not practical for transmission except over very short distances. The attenuation problem can be virtually eliminated, however, through the use of superconductors, which opens up the use of millimeter waveguides for a variety of applications. Superconductor waveguides have been studied previously for low-T_c ($T_c < 18$ K) superconductors (e.g., [6]–[9]). High-T_c ($T_c > 77$ K) superconductors have slightly different properties from low-T_c superconductors, however, and, with T_c greater than liquid nitrogen or even room temperature, also have new applications. In this paper, we study the transmission properties of high-T_c superconductor waveguides.

We first consider the various parameters of high-T_c superconductor waveguides, including carrier frequency and bandwidth, signal attenuation, maximum transmit power, dynamic range, and dispersion. Results show the potential for 100 GHz of bandwidth for transmission over long distances with low attenuation. For example, using existing solid-state transmitters and receivers, waveguides with a carrier frequency of about 120 GHz and 60 GHz of bandwidth would have less than 1 dB/km signal attenuation due to the waveguide and a dynamic range (margin) greater than 70 dB (for a potential of more than 10 million taps). Furthermore, at these frequencies the waveguide would be 2×1 mm in cross section so that a relatively flexible cable may be possible (even brittle materials are relatively flexible if small enough in cross section, and, furthermore, "flexible" superconductors are being developed [10]). Dispersion, however, could limit the maximum data rate per user to 380 Mb/s for distances greater than 1 km (for a single channel without equalization). We then study the possible application of a single waveguide as the transmission medium for a 60 GHz (data rate) local area network.

In Section II, we briefly analyze the various parameters of high-T_c superconductor waveguides. Applications in local area networks are discussed in Section III. Finally, a summary and conclusions are presented in Section IV.

II. Theory

In this section, we briefly study the various parameters of high-T_c superconductor waveguides. The theory of high-T_c superconductors can be very complicated unless numerous approximations are made. Thus, we make some approximations (e.g., carrier frequency much less than the gap frequency [4], see subsection II-E, and temperature $T < 0.6T_c$) so that rough estimates of the above parameters can easily be made.

A. Waveguide Size and Bandwidth

Here we consider a rectangular waveguide using the TE_{10} mode because the rectangular waveguide is simplest to analyze and, in a rectangular waveguide, the TE_{10} mode is the most frequently used mode [11, p. 243]. If the waveguide has dimensions $a \times b$, where $a > b$, then at frequency f

$$\frac{c}{2a} < f < \min\left(\frac{c}{2b}, \frac{c}{a}\right) \tag{1}$$

where c is the speed of light, only the TE_{10} mode will be propagated. The lower frequency $c/2a$ is the cutoff frequency f_c for the waveguide.[1] Thus, the bandwidth of the waveguide is maximum for $b \leqslant a/2$. As shown in subsection

[1]Since in this frequency range only one mode can propagate, we do not consider the problem of inducing multiple modes at energy coupling points (taps), and mode conversion due to possible roughness of the superconductor waveguide surface or the curvature of the waveguide. These effects, however, could increase the attenuation of the waveguide [12].

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II-C, the maximum power in the waveguide increases linearly with b and, therefore, b should be as large as possible (keeping $a > b$). However, it will be shown later (subsection II-F) that the maximum power for $b = a/2$ does not appear to be a practical limitation. Therefore, for maximum bandwidth, we let $b = a/2$, and the bandwidth is [from (1)]

$$B = f_c = \frac{c}{2a}. \tag{2}$$

In practice, since better performance is achieved by not operating near either extreme of the frequency range, a bandwidth of $0.75 f_c$ (from 1.11 f_c to $1.86 f_c$) is usually recommended [11, p. 246]. For example, with $f_c = 75$ GHz, the waveguide has cross section 2×1 mm and the recommended bandwidth is about 56 GHz (83–139 GHz) [5, p. 261]. Note that, at this frequency and above, the waveguide is small enough that it may be relatively flexible.

B. Attenuation

Next, let us consider the attenuation of signals in the waveguide. With the parameters of subsection II-A ($b = a/2$, $f_c = c/2a$), the attenuation of signals due to losses in the waveguide walls at frequency f is given by [11, p. 262]

$$\alpha = 3.1 \times 10^{-7} R_s \left[\frac{f_c\left(1 + (f_c/f)^2\right)}{\sqrt{1 - (f_c/f)^2}} \right] \text{dB/km} \tag{3}$$

where R_s is the surface resistivity of the walls in Ω and f_c is in Hz (most of the results in this paper are rounded to two significant digits).

Consider first a waveguide with walls of normal metal. For example, for a silver (which has the lowest resistivity of normal metals [13, p. 47]) waveguide, the attenuation is given by [from (3)]

$$\alpha_{\text{metal}} = \begin{cases} 11{,}000(f_c/100\ \text{GHz})^{1.5}\ \text{dB/km} & \text{at } f = 1.11\ f_c \text{ (worst case)} \\ 5100(f_c/100\ \text{GHz})^{1.5}\ \text{dB/km} & \text{at } f = 1.86\ f_c \text{ (best case)} \end{cases} \tag{4}$$

at room temperature, $T = 290$ K (at $T = 77$ K, the attenuation is 1/2 of (4) in dB). In most of the results given in the rest of the paper, the cutoff frequency is normalized to 100 GHz ($f_c/100$ GHz), so that the results can easily be determined for frequencies near 100 GHz. Note that the attenuation increases with $f_c^{1.5}$ and, thus, single-mode metal waveguides are impractical for transmission of millimeter wavelength signals over more than a few meters.

For a high-T_c superconductor, using the London two-fluid model [14] (as shown in [15]) with λ_0 (the superconductor's penetration depth at $T = 0$) approximately equal to 10^{-7} m [15] and σ_n (the normal conductivity of the superconductor) approximately equal to 10^5 mho/m (see, e.g., [16]), we can show that

$$R_s \leqslant 5.0 \times 10^{-28} f^2 \Omega. \tag{5}$$

Thus, from (3) and (5), the attenuation is given by

$$\alpha_{\text{s.c.}} = 1.5 \times 10^{-34} \left[\frac{f_c^3\left(1 + (f/f_c)^2\right)}{\sqrt{1 - (f_c/f)^2}} \right] \text{dB/km}$$

$$= \begin{cases} 0.77(f_c/100\ \text{GHz})^3 \text{dB/km} & \text{at } f = 1.11 f_c \\ 0.80(f_c/100\ \text{GHz})^3 \text{dB/km} & \text{at } f = 1.86 f_c. \end{cases} \tag{6}$$

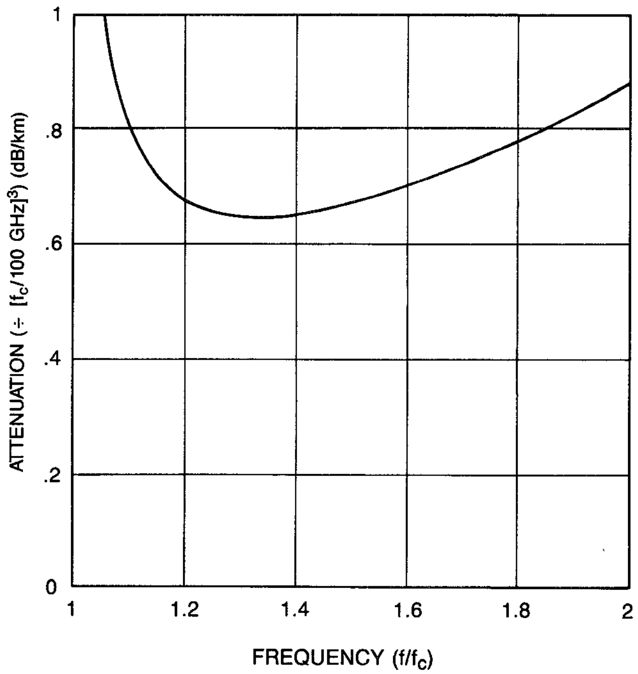

Fig. 1. Attenuation normalized to $(f_c/100\ \text{GHz})^3$ due to wall losses versus frequency.

Note that the attenuation varies with f_c^3 versus $f_c^{1.5}$ for a metal, but that, even at 100 GHz, the attenuation is more than three orders of magnitude less than that of metal.

Fig. 1 shows the attenuation (normalized to $(f_c/100\ \text{GHz})^3$) of a superconductor waveguide versus frequency for $f_c \leqslant f \leqslant 2 f_c$. For a bandwidth of $0.75 f_c$, $1.11 f_c \leqslant f \leqslant 1.86 f_c$, the attenuation is less than $0.81(f_c/100\ \text{GHz})^3$ dB/km. The normalized attenuation varies from 0.80 dB/km at the band edge to 0.64 dB/km at $f = 1.33 f_c$. Thus, while the attenuation is 0.80 dB/km for $f_c = 100$ GHz, at $f_c = 1$ THz (the limit for where the approximations are accurate), the attenuation is 800 dB/km. Thus, except for short distances, rectangular single-mode superconductor waveguides are only practical for carrier frequencies (and, therefore, bandwidths) below a few hundred GHz.[2] Of course, new materials may be developed that have lower attenuation and, therefore, higher frequencies could be practical in a single-mode waveguide. However, it can be shown that, to increase the carrier frequency for a given attenuation by a factor of 10, T_c must be at least 5.3 times higher, or σ_n must be three orders of magnitude lower.

[2] However, the attenuation can be set to arbitrarily small values for frequencies up to a few THz (where the approximations break down) by using a different waveguide structure (an overmoded, circular, superconductor waveguide), but mode conversion due to bends and surface roughness may limit this structure's usefulness.

At 77 K, the inside of the waveguide could be a vacuum or filled with liquid nitrogen, which has lower attenuation than the waveguide walls. If room temperature superconductors ever become available, however, then the attenuation caused by air inside the waveguide may need to be considered, since O_2 and H_2O can cause air losses greater than the wall attenuation. In this case, to keep the air loss negligible, the inside of the waveguide could be a vacuum or filled with gaseous nitrogen.

C. Maximum Power

The maximum power in the waveguide can be limited by two factors: at high enough electric field intensity, arcing occurs between the walls of an air-filled waveguide, and at high enough current, superconductivity no longer occurs. For the recently developed high-T_c superconductors, it can be shown that loss of superconductivity occurs at lower power than arcing. Here we calculate the maximum power due to critical current limitations.

The transmitted power in a waveguide is given by [11, pp. 242 and 261]

$$P_T = \frac{|E_0|^2 ab\sqrt{1-(f_c/f)^2}}{4\eta} \tag{7}$$

where η is the intrinsic impedance of the medium inside the waveguide, and $|E_0|$, the magnitude of the electric field intensity, is given by

$$|E_0| = |J|\eta\left(\frac{2af}{c}\right)\lambda \tag{8}$$

where J is the current density and λ is the superconductor's penetration depth. Thus, with $\eta = 377\ \Omega$, $a = c/2f_c$, $b = c/4f_c$, $\lambda = 10^{-7}$ m (from subsections II-A and -B), and $J = 10^6$ A/cm^2 (see, e.g., [17]), the maximum power due to critical current limitations is given by

$$P_{\max_{\text{current}}} \leqslant \begin{cases} \dfrac{57}{(f_c/100\text{ GHz})^2}\text{ W} & \text{at } f = 1.11 f_c \\ \dfrac{309}{(f_c/100\text{ GHz})^2}\text{ W} & \text{at } f = 1.86 f_c. \end{cases} \tag{9}$$

Note that the maximum power is on the order of watts up to about 1 THz.

D. Device Limitations

Next, we consider the device limitations of currently available (or near-term) transmitters and receivers. In particular, we are interested in the size, cost, maximum output power, maximum frequency, and bandwidth of each device. As the results of subsections II-A, -B, and -C have shown that frequencies up to hundreds of GHz are practical, we consider both vacuum tube and solid-state devices that are capable of operating at those frequencies.

One device is the extended interaction oscillator [18]. This device is very large (as it is a vacuum tube source) and, in large quantities, could cost about \$1000. The maximum output power is on the order of kW's, far in excess of that required for waveguides, with a maximum frequency of 260 GHz. Thus, such a device could be useful if a given application calls for only one transmitter and/or receiver.

Solid-state devices include p-i-n [19], IMPATT [20], and Schottky [21] diodes, Gunn oscillators [22], and HEMT amplifiers [23]. As these devices are solid-state devices, the prices of these devices in large production could conceivably be as low as \$10 to \$50. The output powers are on the order of 100 mW or less, with maximum frequencies as high as 2.5 THz for Schottky diodes [21]. Bandwidths up to 6 GHz [19] and higher are possible.

Finally, we note that while the above devices do not contain superconductors, high-T_c superconductors also open up new possibilities for low-cost high-frequency devices [24].

E. Maximum Carrier Frequency

Although the maximum carrier frequency for superconductor waveguides is mainly limited by the factors discussed in subsections II-B--D, another limitation is the gap frequency [15]. As the frequency approaches the gap frequency, material dispersion and attenuation in the superconductor increase until superconductivity breaks down at the gap frequency. To avoid severe dispersion problems, the maximum frequency should, in general, be less than 10% of the gap frequency [15]. For high-T_c superconductors, the gap frequency is on the order of tens of THz, and, therefore, the maximum frequency should be kept below a few THz. Note that the limitations of subsections II-B--D will prevail before this frequency limit is reached.

F. Dynamic Range

Let us next consider the dynamic range of the superconductor waveguide. The dynamic range is the ratio of the maximum transmit power to the minimum receive power for a given bit error rate and, therefore, is the margin that can be used for attenuation, taps, etc. The minimum receive power for a given error rate is dependent on either thermal noise at low frequencies or quantum effects at high frequencies. However, for $f < 1$ THz, the thermal noise dominates the quantum noise. In particular, let us consider the minimum receive power (and the dynamic range) for a 10^{-9} bit error rate with coherent detection of a phase-shift-keyed signal. In this case, the bit error rate is given by [25]

$$\text{BER} \approx \frac{1}{2}\,\text{erfc}\sqrt{\frac{P_R}{kTB}} \tag{10}$$

where erfc$(\cdot)$ is the complementary error function, P_R is the received signal power, B is the bandwidth, and k is Boltzmann's constant (1.38×10^{-23} j/K). Thus, with $B = 0.75 f_c$ and the maximum power given by (9), the dynamic range (at a 10^{-9} bit error rate) is

$$\frac{P_T}{P_R} = \begin{cases} 106 - 30\log_{10}(f_c/100\text{ GHz})\text{ dB} & \text{at } T = 77\text{ K} \\ 100 - 30\log_{10}(f_c/100\text{ GHz})\text{ dB} & \text{at } T = 290\text{ K}. \end{cases} \tag{11}$$

Noting that solid-state devices have a maximum power of about 100 mW, the dynamic range with these devices is

$$\frac{P_T}{P_R} = \begin{cases} 78 - 10\log_{10}(f_c/100\text{ GHz})\text{ dB} & \text{at } T = 77\text{ K} \\ 73 - 10\log_{10}(f_c/100\text{ GHz})\text{ dB} & \text{at } T = 290\text{ K}. \end{cases} \tag{12}$$

In any system, there will be some losses due to attenuation, receiver noise figure, etc. However, assuming these losses are

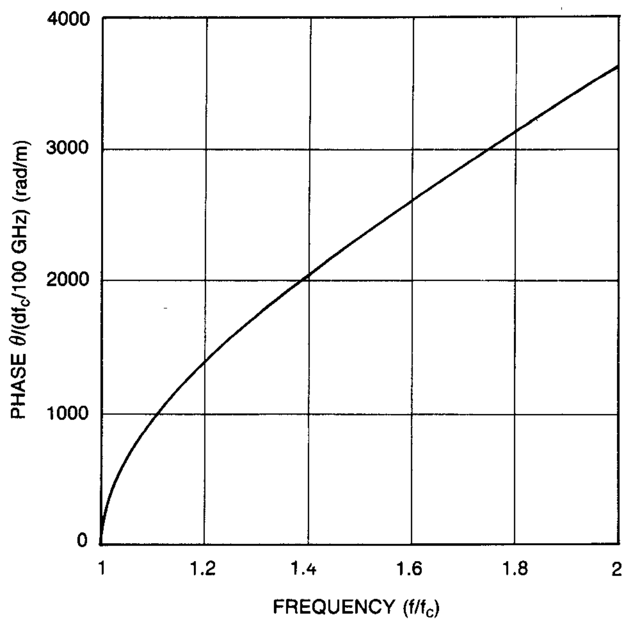

Fig. 2. Phase versus frequency across the bandwidth of the waveguide.

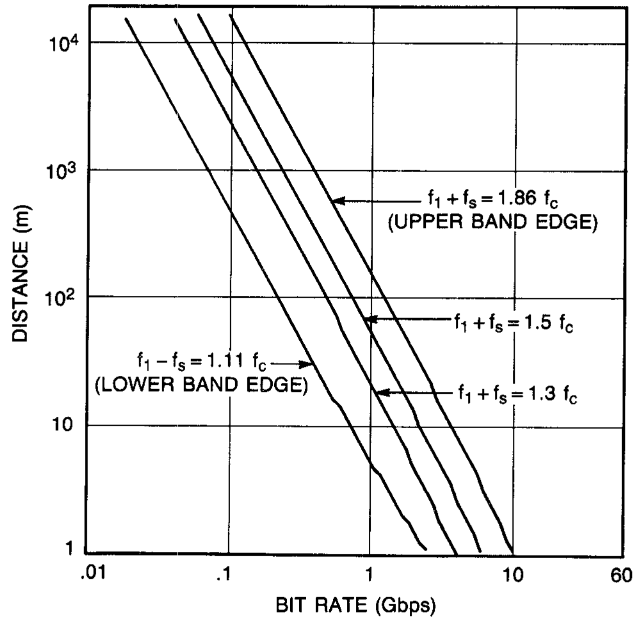

Fig. 3. Maximum distance versus bit rate for which the eye remains open with dispersion due to phase distortion with $f_c = 80$ GHz.

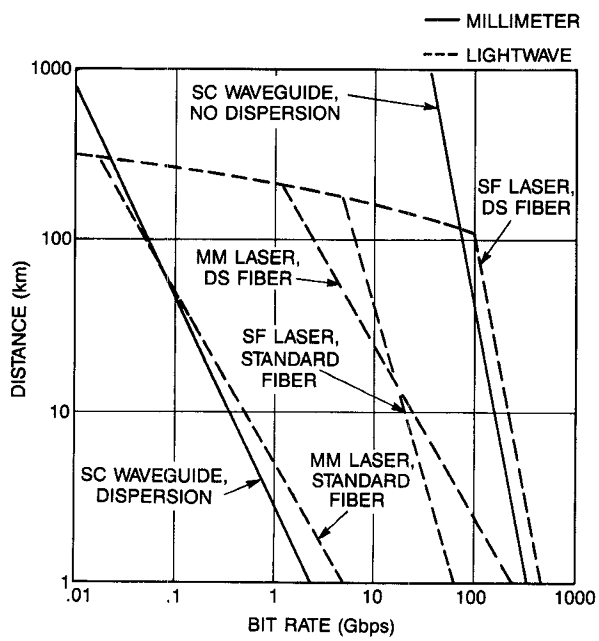

Fig. 4. Comparison of the maximum distance versus bit rate for single-mode rectangular superconductor waveguides and lightwave systems.

relatively small, and noting that the excess loss due to tapping a superconductor waveguide should be negligible (i.e., should be less than the power tapped), the above results show that in excess of ten million taps on the waveguide may be possible (assuming different taps for transmitting and receiving, e.g., frequency-selective taps with different transmit and receive frequencies as in a multihop network [26]). Thus, for all practical purposes, the number of taps on the waveguide is unlimited. Furthermore, with such a large dynamic range, attenuation of the waveguide should not be a concern for distances up to tens of kilometers.

G. Dispersion

Dispersion in single-mode waveguides causes the width of a pulse to become wider with distance traveled. When multiple pulses are sent in sequence, pulse spreading can result in pulse overlap (i.e., intersymbol interference) in wide bandwidth signals transmitted over long distances. Dispersion in the waveguide is caused both by the variation in attenuation versus frequency (which can be shown to be negligible) and a nonlinear group velocity (or phase) versus frequency characteristic. Thus, dispersion results in a bandwidth/distance tradeoff or limitation (which can be overcome by equalization, e.g., dielectric rods [27] or, alternatively, coaxial cables (which are essentially phase dispersionless) can be used [28]). Below, we first consider the phase distortion and then show the bandwidth versus distance tradeoff.

The phase at frequency f and distance d is given by

$$\theta = \frac{2\pi f d}{v_p} = \frac{2\pi f_c d\sqrt{(f/f_c)^2 - 1}}{c} \text{ rad} \tag{13}$$

wheres v_p is the phase velocity [11, p. 451]. The phase versus frequency is shown in Fig. 2.

To study the effect of phase distortion, let us consider a specific example of a raised cosine pulse with frequency spectrum given by

$$P(f) = \begin{cases} \dfrac{1+\cos\left(\pi(f-f_1)/f_s\right)}{2}, & |f-f_1| < f_s \\ 0, & \text{elsewhere} \end{cases} \tag{14}$$

where f_s is the symbol (bit) rate and f_1 is the center (carrier) frequency. For this signal, we can calculate the maximum bit rate (note that, for the signal of (14), the bit rate is one half the signal bandwidth $2f_s$) and distance for which the eye remains open (note that, because of the large margin, we will ignore thermal noise effects on the error

TABLE I
SUMMARY OF ATTRIBUTES

	Lightwave (1.5 μm)	Superconductor Waveguides
Available bandwidth	10 THz	100 GHz
Loss	0.2 dB/km	0.6 dB/km at 100 GHz (for YBaCuO)
Dynamic range at 100 GHz	30 dB	70–100 dB
Excess loss per tap	0.1 dB	negligible

rate, see Appendix I). In particular, for $f_c = 80$ GHz, Fig. 3 shows the maximum distance versus bit rate for which the eye remains open, with dispersion due to phase distortion. Note that at the upper edge of the band, a bit rate of 0.63% of the total bandwidth (0.0063×60 GHz = 380 Mb/s) can be achieved over distances up to 1 km.

H. Comparison to Optical Fiber

Table I compares some of the attributes of superconductor waveguides to those of optical fibers. Fig. 4 shows the maximum distance versus bit rate for lightwave systems [29]–[31] and single-mode rectangular superconductor waveguides with (unequalized) and without (equalized) dispersion. These curves were determined as described in Appendix II.

Fig. 4 shows that, with equalization, the bit rate-distance product for a single-mode rectangular superconductor waveguide is slightly less than that for a single-frequency laser with a dispersion-shifted fiber (where the linear component of the delay versus frequency is zero, but the higher-order components are still present) for distances less than 100 km. However, the superconductor waveguide can maintain a high bit rate with distances in excess of 1000 km. With dispersion, the bit rate-distance product of the single-mode rectangular superconductor waveguide is similar to that of a multimode laser with a standard fiber.

In summary, the results in this section have shown that superconductor waveguides with 100 GHz or more of bandwidth, tens of kilometers in length, and a virtually unlimited number of taps are theoretically possible. With these properties, superconductor waveguides may be competitive with optical fiber.

III. APPLICATION TO LOCAL AREA NETWORKS

As an example application, let us consider the use of superconductor waveguides in a local area network. Here, a single waveguide is considered in a cable that is routed to all users (e.g., a ring). We consider a waveguide with $f_c = 80$ GHz and a bandwidth of 60 GHz. Thus, the maximum power is limited to [from (9)] $57/(80/100)^2 = 89$ W, i.e., the transmit power must be reduced if there are more than 890 transmitters. For $89 \leqslant f \leqslant 149$ GHz, the attenuation due to the waveguide walls is less than 0.40 dB/km [from (6)].

Therefore, for our example assuming frequency selective input taps ($1/N$ loss between transmitter and receiver) with the 60 GHz of bandwidth divided equally among the N inputs (e.g., 6 MHz input with 10^4 inputs),

$$N \leqslant \begin{cases} 10^{10.3-.04L}, & L \leqslant 185 \text{ km} \\ 0, & L > 185 \text{ km} \end{cases} \tag{15}$$

where L is the length of the local area network cable in kilometers. Thus, for $L \leqslant 82$ km, there can be more than ten million users.

If, on the other hand, the 60 GHz bandwidth is time shared among all users (i.e., neglecting dispersion), the maximum number of users is $20\log_{10} N \leqslant 74 - 0.4L$ or $N = 10^{(74-0.4L)/20}$. Thus, 100 users (each with a peak data rate of 60 Gb/s) are possible if $L < 82$ km. If a combination of frequency-division and time-division multiple access is used, the maximum number of users can be increased from 100 to up to 10^7 users, depending on the peak data rate per user.

IV. CONCLUSION

In this paper, we have studied high-T_c superconductor waveguides. Postulating the existence of such devices in the future, we have determined the characteristics of such waveguides based on recently developed high-T_c superconductors. The advantage of superconductor waveguides were shown to be potentially wider dynamic range relative to optical systems (providing a virtually unlimited number of taps or reducing the need for signal amplification) with 100 GHz or more of bandwidth. We then discussed applications of superconductor waveguides in local area networks, where tens of Gb/s of throughput are available with up to a million or more users.

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APPENDIX I
EYE CLOSURE WITH DISPERSION

With pulse frequency spectrum $P(f)$ given by (14) and channel frequency response $H(f)$ given by

$$H(f) = 10^{\alpha_{s,c} d/20} e^{j\theta} \tag{A1}$$

where θ is given by (13), the received signal for transmission of a single pulse is

$$x(t) = F^{-1}\{P(f)H(f)\} \tag{A2}$$

where F^{-1} denotes the inverse Fourier transform. Thus, the eye will always remain open if

$$|x(t_0)| > \sum_{\substack{i=-\infty \\ i \neq 0}}^{\infty} |x(t_0 + i/f_s)| \tag{A3}$$

where t_0 is the sampling time of the pulse at the receiver. In our analysis, we calculated the maximum dispersion for which (A3) holds.

Appendix II
Distance Versus Bit Rate Calculations

For the lightwave results, with a fiber with 0.2 dB/km attenuation, a laser with $P_T = 1$ mW, and $P_R = 7\times10^{-5}B$ mW for a 10^{-9} bit error rate [29], [30], the loss limit is given by

$$L_1 = -50\log_{10}(7\times10^{-5}B) \tag{A4}$$

where L_1 is in kilometers and B is in Gb/s (here we assume that the bandwidth is approximately equal to the bit rate). The dispersion limits are: 1) for a multimode (MM) laser with a standard fiber, $L_2 = 5/B$ [31]; 2) for a MM laser with a dispersion-shifted (DS) fiber, $L_2 = 240/B$ [31]; 3) for a single-frequency (SF) laser with a standard fiber, $L_2 = 4000/B^2$ [29]; and 4) for a SF laser with a DS fiber, $L_2 = 10^8/B^3$ [29]. Thus, for these four lightwave systems, the distance is the minimum of L_1 and L_2.

For a single-mode rectangular superconductor waveguide, with $P_T = 100$ mW, $P_R = 7.2\times10^{-8}B$ mW at $T = 290$ K [from (11)], and wall attenuation given by (6), the loss limit is given by (with $f_c = 0.75B$),

$$L_1 = -5.2\times10^6\frac{\log_{10}7.2\times10^{-10}B}{B^3}. \tag{A5}$$

The dispersion limit for $f_1 + f_s = 1.86f_c$ is shown in Fig. 3 and is approximately given by

$$L_2 \approx 4.1\times10^{-5}\left(\frac{0.75f_c}{f_s}\right)^2 \tag{A6}$$

with f_c in GHz. Note that, for fixed f_s, the distance increases with f_c, while the loss limit (for wall attenuation) with variable f_c,

$$L_1 = -1.2\times10^7\frac{\log_{10}7.2\times10^{-10}f_s}{f_c^3} \tag{A7}$$

(note that, for the raised cosine pulse of (14), the equivalent noise bandwidth is equal to the bit rate) decreases with f_c. Thus, the maximum distance with both attenuation and dispersion can be shown to be given by

$$L = 1.12\left(\frac{-\log_{10}7.2\times10^{-10}f_s}{f_s^3}\right)^{2/5} \tag{A8}$$

with

$$f_c = 220\left(-f_s^2\log_{10}7.2\times10^{-10}f_s\right)^{1/5}. \tag{A9}$$

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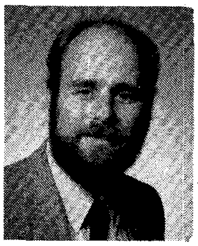

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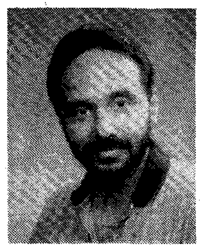

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