Effects of Multiple Splice Reflections in Fiber Optic AM CATV Transmission Systems

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ABSTRACT

Reflections in fiber optic AM CATV transmission systems are an important source of noise. Mechanical splices always introduce some reflection, which is a function of temperature. For two splices, the degradation in Carrier to Noise Ratio (CNR) is related to the magnitude of the co-polarized reflections. For multiple splices, the CNR degradation is related to the sum of the reflection contributions from every combination of splice pairs in the system, as well as reflection from Rayleigh scattering. The reflection induced noise also depends on laser characteristics, such as chirp and modulation index. Measurements using two reflections show excellent agreement with theory. Measurements using eight Fibrlok™ mechanical splices at temperatures ranging from -40 C to +80 C confirm the theory for the multi-splice case, with only minor decline in system CNR.

INTRODUCTION

Single-mode optical fiber is currently used as the backbone transmission medium in many AM CATV applications. The fiber link is typically 10 to 30 km long, with splices approximately every 2 km. These splices can introduce noise into the system in a variety of ways. In the absence of reflections, both mechanical and fusion splices can introduce modal noise if the splices are close together[1] as might be the case for laser pigtails, cable repairs, or patch panels. If the splices have some reflection, interferometric phase-to-intensity conversion from a pair of reflections can convert laser phase fluctuations to intensity noise[2].

We are primarily interested in the effects of splice reflections on system noise. While both fusion and mechanical splices typically have low reflections at moderate temperatures, reflections from mechanical splices may become important at extreme temperatures. Reflections occur at a change in index of refraction. The reflectance of a mechanical splice is the sum of the two reflections, which occur at each fiber/gel interface, and an interference term, which describes either constructive or destructive interference between the two reflections within a splice. The index of refraction of the gel is a function of temperature, and thus the reflectance of mechanical splices varies with temperature. Moreover, as a splice expands and contracts with temperature, the interference term will vary as well. Other factors, such as end angle, surface quality, and splice loss reduce the amount of reflected light that is captured by the fiber core. The reflections can be reduced in a variety of ways, such as using angled cleaves or improved index matching gels. By developing a model for multiple splice reflections and their influence on noise, system performance can be predicted for actual splice reflections. This will aid in determining whether a mechanical splice is suitable for fiber optic CATV systems.

SINGLE CAVITY CASE (TWO SPLICE SYSTEMS)

In a system that has two splices, the splices will form a reflection cavity. In this case, the total system noise consists of the baseline noise and the noise introduced by the cavity:

$$CNR_{sys} = -10\log\left[10^{-CNR_{cav}/10} + 10^{-CNR_{base}/10}\right]. \quad (1)$$

Here CNR_{sys} is the total system noise, CNR_{cav} is the noise introduced by the cavity and CNR_{base} is the baseline noise of the system without the cavity. CNR_{base} will be limited by multipath interference caused by double Rayleigh backscatter[3].

The CNR of the cavity (CNR_{cav}) can be determined by measuring CNR_{sys} and CNR_{base}, and calculating the "backed out" CNR_{cav}. Thus,

$$CNR_{cav} = -10\log\left[10^{-CNR_{sys}/10} - 10^{-CNR_{base}/10}\right]. \quad (2)$$

The measured CNR_{cav} can be compared to a theoretical model[4]:

$$CNR_{cav} = 10\log\left[\frac{\sqrt{2\pi}}{8}\frac{m^2}{R_{12}}\frac{B_{1/2}}{B_N}\right] \quad (3a)$$

$$= 10\log\left[\frac{\sqrt{2\pi}\, m^2}{16\sqrt{\ln 2}}\frac{B_{FWHM}}{B_N}\right] - \mathcal{R}_{12} \quad (3b)$$

where:

CNR_{cav} is the theoretical CNR of the cavity,
$B_{1/2}$ is the 1/e bandwidth of the laser spectrum,
B_{FWHM} is the full width at half maximum of the laser spectrum,
B_N is the noise bandwidth for cable TV (4 MHz),
m is the modulation index,
R_{12} is the ratio of the twice reflected power to the main signal power at the receiver,
$\mathcal{R}_{12} = 10\ \log(R_{12})$.

Equation 3 assumes that the splices are separated by at least several meters of fiber, and that the reflected light has the same polarization as the non-reflected light. Equation 3 also assumes a Gaussian optical spectrum with a width much larger than the CATV modulation frequency. This results in a flat noise response over the band. A small correction factor must be used to correct for the Gaussian line shape of the noise introduced by a narrow line laser. For a narrow line laser, and carrier frequency f, the CNR will be given by

$$CNR_{cav} = 10\log\left[\frac{\sqrt{2\pi}}{16\sqrt{\ln 2}}\frac{m^2}{R_{12}}\frac{B_{FWHM}}{B_N}e^{2f^2\ln(2)/(B_{FWHM})^2}\right] \quad (4)$$

The width of the laser diode spectrum, B_{FWHM} or $B_{1/2}$, is dominated by the laser chirp. The chirp is a shift in the wavelength as the drive current changes. Thus the width of the laser spectrum will depend on the level of modulation. The chirp characteristics of laser diodes vary widely from device to device.

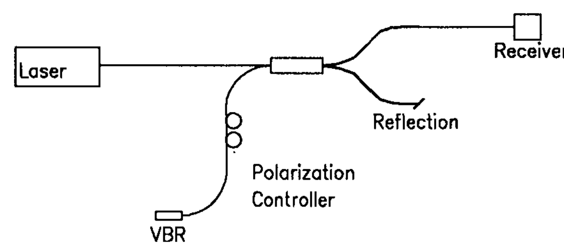

Figure 1. Experimental setup for the single cavity test. Two reflections were placed on opposite ends of a coupler. The fixed reflection is a cleaved fiber immersed in oil, and the variable reflection is a Variable Back Reflector (VBR). Figure 5 shows the measurement system.

Experiment:

Our experimental setup is shown in Figure 1. The reflection cavity consisted of a coupler with one end cleaved and immersed in index matching oil (with an index chosen to provide the appropriate level of reflection), and the other end spliced to a variable back reflector (VBR). The polarization controller was adjusted for maximum system noise, which occurs when the incident and reflected waves are co-polarized. The $\mathcal{R}_{12}$ term includes round trip cavity losses through the coupler, taking into account the coupler insertion loss. We used two different lasers: one high chirp, and one low chirp. The laser spectral widths were measured using a scanning Fabry-Perot interferometer at the rf drive levels used in the test. The spectral widths of the lasers were $B_{FWHM} = 6180$ MHz and $B_{FWHM} = 780$ MHz for the high and low chirp lasers, respectively. A CATV multi-channel generator produced 42 CATV carriers, from 55.25 MHz to 325.25 MHz. We measured CNR_{sys} and CNR_{base} with a spectrum analyzer for both lasers at three frequencies (55.25 MHz, 187.25 MHz, and 325.25 MHz) with a variety of cavity reflection levels. We then plotted the computed backed out CNR_{cav} from Equation 2 along with the theoretical CNR_{cav} from Equation 3. We found excellent agreement with theory (usually within ±2dB) for $\mathcal{R}_{12} > -70$ dB. For very small reflections, $CNR_{\text{cav}} > 65$ dB. In this case, CNR_{sys} and CNR_{base} are nearly equal, and Equation 2 becomes very sensitive to measurement error. Equation 3 gives a reasonably accurate estimate for the effects of a reflection cavity on CNR.

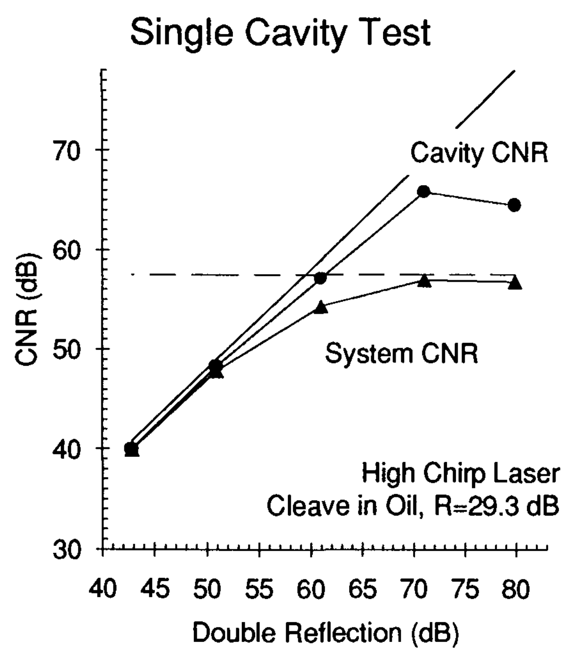

Figure 2. Single cavity results for a high chirp laser at 187.25 MHz. The dashed line is CNR_{base}. The solid line is the theoretical CNR_{cav}. The circles and triangles are measured values for cavity CNR and system CNR respectively.

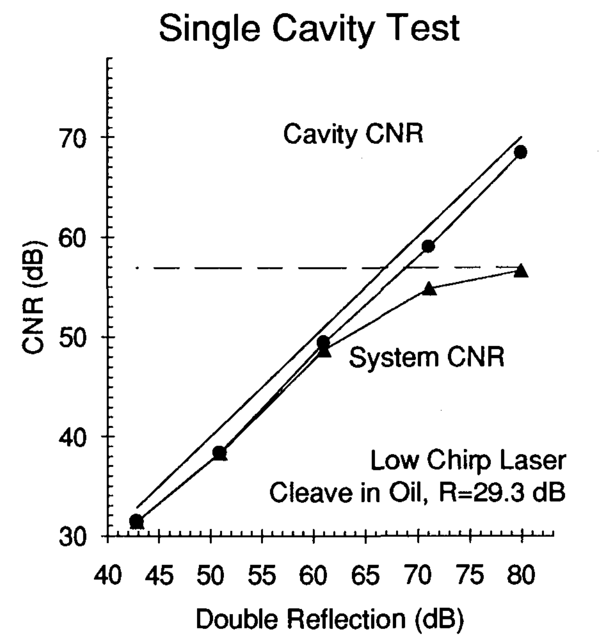

Figure 3. Single cavity results for a low chirp laser at 187.25 MHz. The dashed line is CNR_{base}. The solid line is the thoeretical CNR_{cav}. The circles and triangles are measured values for cavity CNR and system CNR respectively.

Figures 2 and 3 show typical results from our experiment. The baseline is the measured result for the system without a reflection cavity. As R_{12} decreases, the system CNR approaches the baseline. Figure 2 shows the result for a high chirp laser and Figure 3 shows the result for a low chirp laser. The cavity introduces more noise with the low chirp laser than with the high chirp laser just as Equation 3 predicts.

Equation 3b shows that CNR can be improved by increasing the laser modulation (m), or by using a higher chirp laser (B_{FWHM}).

Both of these effects were confirmed by our measurements. If high chirp lasers are selected, CNR degradation due to reflections is substantially reduced.

Our main interest with Equation 3b is the $\mathcal{R}_{12}$ term. CNR introduced by the cavity follows $\mathcal{R}_{12}$: a 1 dB improvement in $\mathcal{R}_{12}$ results in a 1 dB improvement in CNR_{cav}. Note that $\mathcal{R}_{12}$ is almost independent of the positions of the two reflection points. The only dependence on position is due to the round trip cavity losses from fiber attenuation. Thus widely separated splices are slightly better than closely spaced splices, ignoring Rayleigh scattering.

MULTIPLE CAVITY CASE (MULTIPLE SPLICE SYSTEMS)

For multiple cavities, the noise term can be described as a summation over all of the terms generated by the double reflections[5]. Each cavity will add by Equation 1. Combining with Equation 4 we get

$$CNR_{\text{cav}} = 10\log\left[\frac{\sqrt{2\pi}\, m^2}{16\sqrt{\ln 2}}\frac{B_{FWHM}}{B_N} e^{2f^2\ln(2)/(B_{FWHM})^2}\right] - 10\log\left[\sum R_{mn}\right] \quad (5)$$

Here, the subscripts n and m refer to the individual splices, and the summation is over all possible cavities formed. For N reflection points, there are $N(N\text{-}1)/2$ terms in the summation: for 8 splices there are 28 terms. Each R_{mn} includes both reflections and the round trip cavity losses. For reflections R_m and R_n,

$$R_{mn} = \frac{1}{2} R_m R_n 10^{-2\alpha\ell_{mn}/10}, \quad (6)$$

where α is the fiber loss in dB/km and ℓ_{mn} is the separation distance in km. The factor of ½ is included to account for random depolarization by long pieces of fiber[6]. If the splices are closely spaced, this factor will not be included. Using Equation 5, we can compute the CNR for any combination of splice reflections.

For convenience in reporting results we define an "Average Reflection":

$$R_{ave} = \left[\frac{\sum_{n=1}^{N}\sum_{m=n+1}^{N} R_m R_n}{N(N-1)/2}\right]^{1/2}. \quad (7)$$

This is the average of the $R_m R_n$ terms.

Effects of Rayleigh Backscatter:

For a system with small reflections, the fiber Rayleigh backscatter will be much larger than the splice reflections. Light reflected from a splice will see Rayleigh backscatter from the fiber between splices in addition to the other splice reflections. The summation in Equation 5 becomes:

$$\sum R_{mn} = \sum_{m=1}^{N-1}\sum_{n=m+1}^{N} \tfrac{1}{2} R_n R_m 10^{2\alpha\ell_{nm}/10} + \frac{S\alpha_s}{4\alpha'}\sum_{i=1}^{N} R_i\left[\left(1-e^{-2\alpha'\ell^+}\right)+\left(1-e^{-2\alpha'\ell^-}\right)\right]. \quad (8)$$

S is the amount of scattered light captured by the fiber (S=.0015 at 1300 nm), α' is the fiber loss coefficient $[\alpha' = \alpha\ln(10)/10]$ and α_s is the Rayleigh scattering coefficient, i.e., the fraction of light lost due to scattering (for an ideal fiber, $\alpha_s = \alpha' = .076\ \text{km}^{-1}$)[3]. $\ell^{\pm}$ is the length of fiber in the link in the forward (+) or backward (-) directions from the splice. If the splices are evenly spaced by distance $\Delta\ell$, $\ell^+ = \Delta\ell(N+1-i)$ and $\ell^- = \Delta\ell i$.

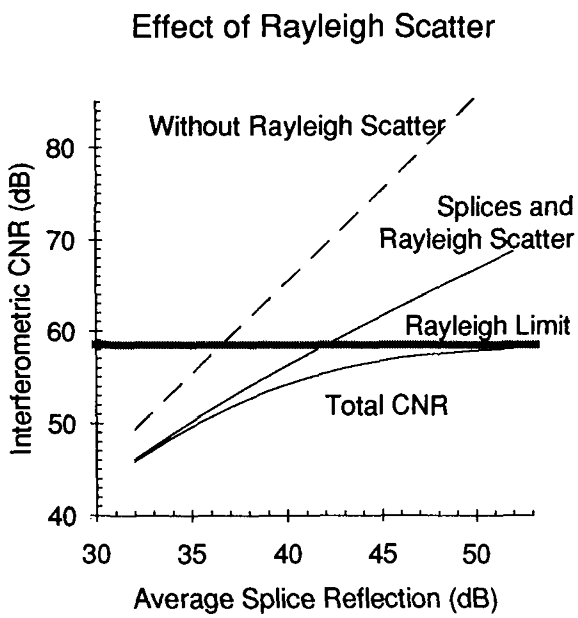

Figure 4. Interferometric CNR for an eight-splice system with and without Rayleigh scatter. The horizontal line is the limit of system CNR due to double Rayleigh backscatter in the absence of any other reflections, for the system used in our test. The total interferometric CNR approaches this limit.

Figure 4 compares the results for an eight-splice system, with and without the Rayleigh scattering terms from Equation 8. The result for the case ignoring Rayleigh scattering is a straight line (dashed in Figure 4). Including Rayleigh scatter adds a slight curve to the line and reduces CNR (the middle curve). The horizontal line is the limit of system CNR due to double Rayleigh backscatter scatter in the system under test (B_{FWHM}=1040 MHz, m=0.063, length=20 km). Using this value as the limiting CNR_{base} in Equation 1, gives the total interferometric CNR, the bottom curve in Figure 4. At very small reflections, Rayleigh scattering dominates the total noise term. As the splice reflections become large, Rayleigh scattering becomes less important, and the total CNR approaches the dashed line asymptotically.

Multi-splice experiments:

Our experimental setup for the multiple cavity test is shown in Figure 5. Nine 2.2 km spools of fiber were spliced together by eight Fibrlok™ mechanical fiber optic splices. All cleaves were made with a high quality York cleaver, and the cleaves were checked for flatness and angle using an interferometer. All cleave angles were less then 1°, ensuring the highest possible reflections in the splices. (This was done to generate worst case noise in the system.) The splices were stored in a splice tray and placed in a temperature cycling chamber. An OTDR was used to measure the splice

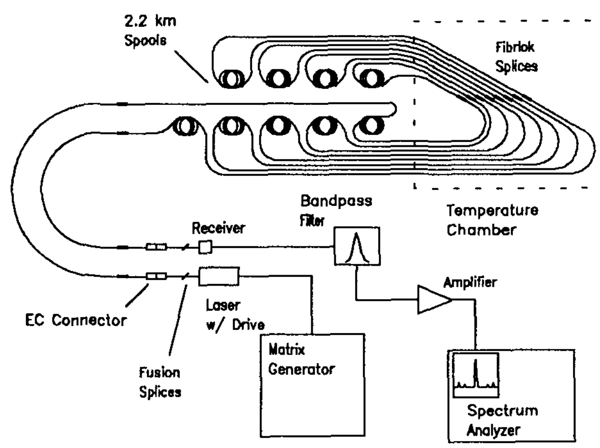

Figure 5. Experimental setup for the multi-splice experiment.

reflections at each temperature: -40 C, -20 C, 0 C, 20 C 40 C, 60 C, 80 C. The measured values for $\mathcal{R}_{ave}$ [$\mathcal{R}_{ave}$=10 log(R_{ave})] and ΣR_{nm} from Equation 8 at each temperature are shown in Table 1. Room temperature values are not shown because the reflections were too small to be seen with the OTDR. Again, a CATV multi-channel generator produced 42 CATV carriers, from 55.25 MHz to 325.25 MHz, and we measured CNR_{sys} with a spectrum analyzer for both lasers at three frequencies (55.25 MHz, 187.25 MHz, and 325.25 MHz) at each temperature. We used the room temperature measurement (essentially no reflections) for CNR_{base}. We also measured system noise for a continuous 20 km piece of fiber at room temperature with a very similar result. The spectral widths of the lasers were $B_{FWHM} = 6180$ MHz and $B_{FWHM} = 1040$ MHz for the high and low chirp lasers, respectively.

Temp	$\mathcal{R}_{ave}$(dB)	ΣR_{nm}(dB)
-40	-39.1	-62.2
-20	-41.8	-65.1
0	-47.7	-71.4
40	-50.3	-74.2
60	-45.2	-68.7
80	-42.2	-65.4

Table 1.

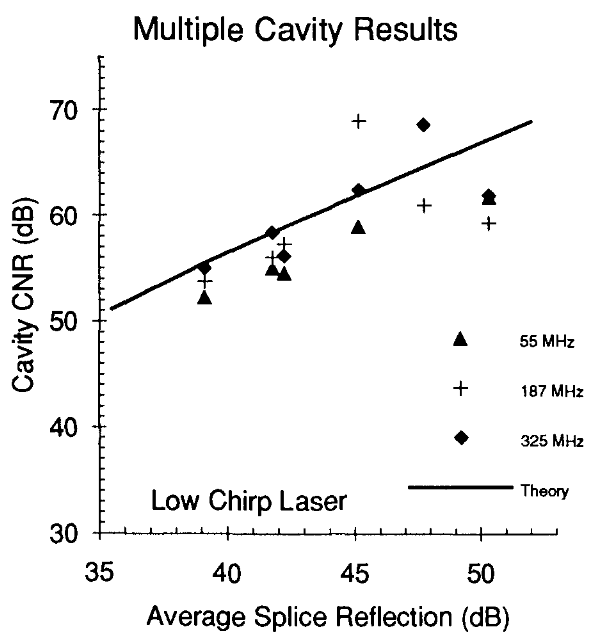

Figure 6. Measured and theoretical results for cavity CNR using a low chirp laser (1040 MHz linewidth). The theoretical result was calculated at 187.25 MHz. Theoretical curves for other frequencies are very close to this result.

We computed the CNR expected from the multiple splice test and compared the results to the measured values. Reasonable agreement with theory was achieved; the largest deviation in CNR_{sys} between theory and measurement was less than 1 dB. For the high chirp laser, CNR_{sys} was very close to CNR_{base}, so that the effective multi-cavity CNR_{cav} was very large (>60 dB). Results for this low chirp laser are closer to the predicted values, since the CNR_{cav} is lower than with the high chirp laser. There is some frequency dependence of the computed results, and the measured results follow the same trend.

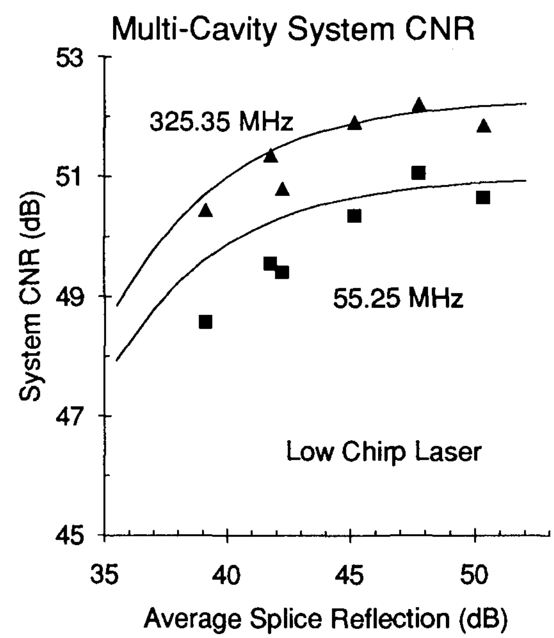

Figure 7. Measured and theoretical results for system CNR using a low chirp laser (1040 MHz linewidth).

Figure 6 shows the CNR_{cav} as a function of average splice reflectance for the low chirp laser. Figure 7 shows the measured and calculated results for the system CNR as a function of average splice reflectance for the low chirp laser. The calculated results agree well with the measurements. Figure 8 compares the two lasers that were used. The high chirp laser system can tolerate much larger reflections before a serious degradation in performance occurs.

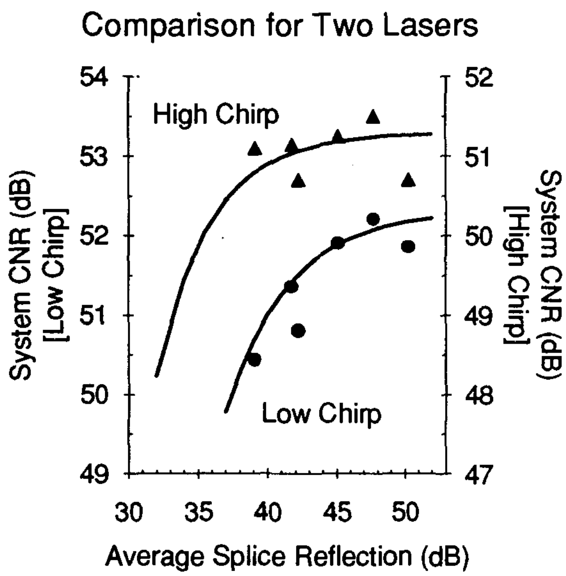

Figure 8. Measured and theoretical results for two lasers. The low chirp laser had a 1040 MHz linewidth; the high chirp laser, 6180 MHz.

Figure 9 shows the effect of changing the number of splices in the system and changing the spacing between the splices. The splices are spaced evenly throughout the link. A larger spacing between splices increases both the Rayleigh scatter and the round trip loss, so the net result is very little length dependence. It is important to note that the cavity CNR is much better if a high chirp laser is used. Cavity CNR with N splices and the low chirp laser will be worse than the cavity CNR with the high chirp laser and 3N splices. With eight splices in the system, the cavity CNR remains above 59 dB even for very long lengths, if a high chirp laser is chosen.

SYSTEMS WITH COUPLERS

Our single cavity test used a coupler to introduce controlled reflections. In an actual system, couplers may be used to construct a passive distribution network. Reflections in such systems introduce some interesting system noise effects that have not been discussed previously. These effects result in some new considerations for network design. A coupler can act as an effectively one-way reflective

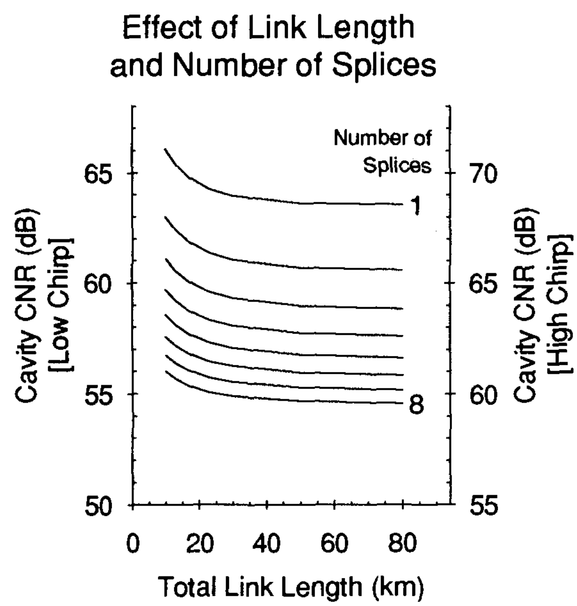

Figure 9. Theoretical results as a function of total link length for different numbers of splices. The splices are evenly spaced within the link. The calculation used a carrier frequency of 55.25 MHz and a splice reflection of -39 dB. The laser linewidths were 1040 MHz and 6180 MHz for the low and high chirp lasers, respectively.

element. That is, light travelling in one direction sees a reflection, but light travelling in the other direction does not. As a result, the locations of the reflection and the coupler become very important.

Consider a system containing a coupler with an unterminated output port. This port will generate a reflection of -14.7 dB (with a perfect cleave). Since the light must pass through the coupler twice (with a 3 dB insertion loss in each direction) the total reflection will be -20 dB back toward the laser. Since the lasers are typically isolated, the feedback into the laser will not be problematic unless the reflection is very large. Thus this single reflection will not be a problem if the coupler is several meters from the laser. However, if the coupler is far from the laser, the fiber between the coupler and the laser will reflect some of the light by Rayleigh backscatter. In this case there is a reflection cavity with reflections of -20 dB and -32 dB, degrading CNR. This shows that the location of the coupler is important and there is an advantage in placing the coupler close to the laser. On the other hand, if the coupler has an unterminated input port, the situation is reversed, and the coupler should be placed near the receiver.

This position dependence is confirmed by experiment. A coupler with a variable reflector on one of the output leads was placed in the system near to the laser. The unused input lead was terminated with low reflection. The system noise in this case was independent of reflection level even for reflections as high as -4.2 dB. When 2 km of fiber was spliced between the laser and the coupler, the noise became sensitive to the magnitude of the reflection. For a reflection of -4.2 dB, the backed out CNR_{cav} was approximately 50.5 dB. For a reflection of -15.4 dB the CNR_{cav} was 57 dB.

In a similar experiment, the unused output port was terminated and the unused input port had a reflector. When 6.4 km of fiber was placed between the coupler and the receiver, the noise level became sensitive to the reflection. For -4.2 dB reflection $\mathrm{CNR_{cav}}$ was 46.5 dB and for -15.4 dB reflection, CNR_{cav} was 54.1 dB.

In an installed system, the unused input ports can be permanently terminated with low reflection ends. The return loss for a factory terminated 3-port coupler is typically in the range of -45 dB to -55 dB. The output ports however, may need to be reconfigured or repaired. In such circumstances the reflections could easily be -14 dB when fibers are disconnected or cleaved. This condition could cause excessive noise in receivers attached to the coupler's other output legs. Thus in a passive video distribution network, designers and installers need to be aware of how reflections in one output leg can affect the noise in other output legs.

CONCLUSION

The model presented in equations 3 and 5 is useful for predicting the system noise effects from splice reflections. The most accurate results were cases of the smallest CNR_{cav},with decreasing accuracy as CNR_{cav} increases. When calculating the effects of small reflections on the system noise, Rayleigh scattering terms must be included to get accurate results. For cases of very small reflections, the contributions from equations 3 and 5 are very small and other effects dominate. Since our measurements were made over several hours, or in the multiple cavity case two days, the measurements could be influenced by a variety of other factors: laboratory temperature, operator consistency, instrumentation drift, repeatability of the connectors on the sources, feedback into the laser, and others. Several measurements taken at room temperature over the course of the two days of testing show variations in CNR_{sys} of up to 0.3 dB.

The laser linewidth is an important consideration for the design of a low noise CATV system. A large FWHM laser spectrum (several GHz) is advantageous for the reduction of noise. The noise introduced into current CATV transmission systems by reflections in the fiber link will be minimal for $\Sigma R_{mn} < -65$ dB, and will be negligible for $\Sigma R_{mn} < -70$ dB even for a low chirp laser. For a high chirp laser, no substantial CNR degradation will occur even with relatively large reflections. With proper engineering, system design and installation, reflection induced noise will be minimal.

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