Influence on the bandwidth

Dependencies of bandwidth of polymer optical fiber for MOST systems

This article shows that the bandwidth of a polymer optical fiber (POF) cannot be regarded as an autonomous parameter to quantify its high frequency performance. Thus the question will be answered, what are the additionally required details to be linked to a bandwidth value.

By Prof. Dr. Jürgen Krapp

A difficulty of polymer optical fibers (POF) is that they suffer significantly from intermodal dispersion. This means that if an optical pulse is launched into such a fiber, the optical power in the pulse is distributed over all (or most) of the modes of the fiber. Each of the modes that propagate in the POF travels at a slightly different speed. As a consequence of that, the modes in a given optical pulse arrive at the fiber end at slightly different times, thus causing the pulse to spread out in time with additionally increased rise and fall times as it travels along the fiber. This effect reduces the data rate transmission capabilities, i.e. decreases the transmission bandwidth.

In consideration of the fact, that the high frequency performance and consequently the information-carrying capacity of the POF do not only depend on its own parameters like numerical aperture and its length, the outstanding question is, which other operating and environmental factors influence the bandwidth value and how much. Additionally, from the perspective of the system designer a certain value of the bandwidth of a POF can only be exploited entirely if the underlying transfer function is known.

The term bandwidth has a different meaning depending on its application in the optical or electrical domain. The definition of the optical bandwidth is normally done in terms of the –3dB-frequency, which is the modulation frequency at which the optical power has fallen to one-half the value of the zero frequency modulation (dc-value). Thus, „–3 dB optical“ means a 50 percent optical power reduction. However, the electrical bandwidth is related to that frequency at which the received electrical power has dropped to one-half of its dc-value.

Under the assumption that the transfer function has a definite characteristic the relation of the electrical to the optical bandwidth can be calculated. In case of a Gaussian shaped transfer function the electrical bandwidth $B_{3dB\ ele}$ is related to the optical bandwidth $B_{3dB\ opt}$ by

$$B_{3dB\ opt} = \sqrt{2} \cdot B_{3dB\ ele} \qquad (1)$$

A system's temporal performance is often specified by either pulse duration or rise time. Which one of these parameters is appropriate depends on the application.

Obviously, pulse width, rise time and bandwidth are related quantities. Mathematically, the step response of a linear system can be obtained by integrating its impulse response. Symmetrical pulse responses without tails or ringing can be approximated by a Gaussian shape. As a consequence of that, they can be regarded as the response of a Gaussian low pass filter. The step responses of Gaussian systems have a rise time $t_{10–90}$ (10 – 90 %) that is only ten percent longer than the FWHM of pulse response and the rise time $t_{20–80}$ (20 – 80 %) is approximately 71 percent of the FWHM pulse response. For this case additionally the relation to the electrical bandwidth is

$$t_{20-80} = 0.222 / B_{3dB\ ele} \qquad (2)$$

In the essence that means, that besides clarifying the type of bandwidth (optical or electrical) the characteristic of the system's transfer function has to be known in order to convert the bandwidth value to the suitable temporal parameter.

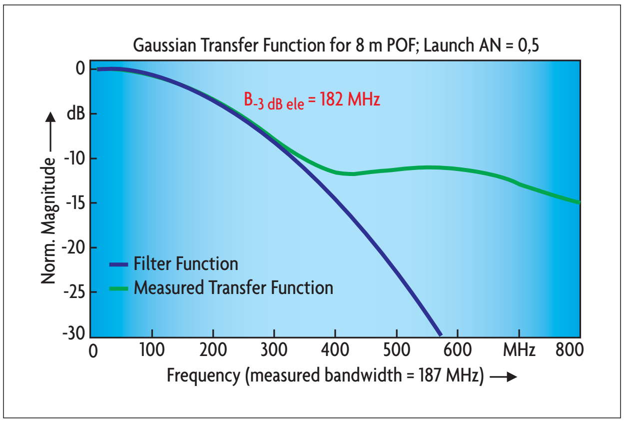


Figure 1. Measured transfer function of Mitsubishi Rayon POF and its Gaussian approximation.

Investigation of POF transfer characteristic

Frequency domain measurements yield information on amplitude-versus-frequency response and phase-versus-frequency response. These data are usually more useful for system designers than time domain pulse measurements, especially if equalization techniques have to be performed on the detected signal at the receiver. The baseband frequency response is found from the ratio of the sine wave at the output and the input of the fiber.

There are three strong advantages of the measurement technique in the frequency domain:

- The fiber transfer function is found directly and can be used to evaluate the response to any arbitrary input signal by Fourier-transforming the data.
- Photodetector linearity over a wide range is not required as in the time domain because of the small signal modulation about a constant average light level.
- The output signal can be received within an extreme narrow measurement bandwidth that reduces the influence of receiver noise significantly and makes the detection of little optical powers possible, e.g. at the end of long fibers.

For any linear system the transfer function can be expressed by the central moments M_m of its impulse response as (3)

$$H(\omega) = A \cdot \exp\left[-j\omega t_C - \frac{\omega^2}{2}\sigma^2 + j\frac{\omega^3}{6}M_3 + \frac{\omega^4}{24}\left(M_4 - 3\sigma^4\right) \pm \ldots\right]$$

where A is area, t_C is the central time, i.e. t_C corresponds to the pulse delay, $\sigma^2 = M_2$ is the variance of the impulse response.

Figure 1 shows the measured transfer function of „Mitsubishi Rayon Heat Resistant“ POF of 8 m length using a launch aperture of AN = 0.5. The figure reveals that the POFs transfer function can be approximated at least up to the bandwidth by a Gaussian function. This is also valid for other fiber lengths and other launch apertures.

For a Gaussian transfer function all odd central moments (M_3, M_5, ...) of the Gaussian pulse response are zero for symmetry reasons. The even central moments of a Gaussian pulse are given by

$$M_m = \sigma^m \cdot 1 \cdot 3 \cdot 5 \cdot \ldots \cdot (m-3) \cdot (m-1) \quad (4)$$

Thus, because of

$$M_4 = 3\sigma^4 \quad (5)$$

etc., all terms in the exponent of Eq. (3) of third order and above are zero for a Gaussian transfer function.

Consequently, if we disregard fiber attenuation (i.e. A = 1) and delay time (i.e. $t_C = 0$), a Gaussian transfer function given as

$$H(f) = \exp\left[-\left(\frac{f}{1.7 \cdot B_{-3dB}}\right)^2\right] \quad (6)$$

is a useful approximation for the polymer optical fibers transfer function. In Eq. (6) B_{-3dB} is the electrical –3dB-bandwidth being used instead of the rms-width σ of the impulse response. B_{-3dB} can either be determined by measurement or approximated by the relation Eq. (7) given in the next chapter.

Influence of fiber length launch aperture

For a polymer optical fiber the deterioration of bandwidth originates from modal dispersion. Material dispersion effects can be neglected. The analysis shows, that the bandwidth is not only a function of the length of the fiber but also depends on the type of optical source used. In real systems bandwidth will decrease less rapidly after a certain initial length because of mode coupling and differential mode loss. In the fiber the coupling of energy from one mode to another arises from structural imperfections, fiber diameter and refraction index variations, and cabling-induced microbends.

The mode coupling has the tendency to average out the different propagation delays associated with the modes, and thus reducing intermodal dispersion. The result of this phenomenon is that, after a certain coupling length L_C, the bandwidth will change from L^{-1} dependence to $L^{-0.5}$ dependence. Because one dependency approaches the other with increasing fiber length L very slowly the bandwidth-length dependence can be regarded according to the empirical relation

$$B_{-3dB} = B_0 \cdot L^{-q} \quad (7)$$

The parameter q indicates the amount of mode mixing in the fiber and ranges between q = 0,5 for maximum mode mixing (if after the fiber coupling length L_C the dynamic mode equilibrium is reached) and q = 1 in case without mode mixing.

Figure 2 shows the measured bandwidth versus fiber length for launch apertures between 0.18 and 0.56. The bandwidth-length dependency is approximated for each launch aperture by a potential regression according to Eq. (7). All regressions estimate the measured data within ±5 % accuracy. The

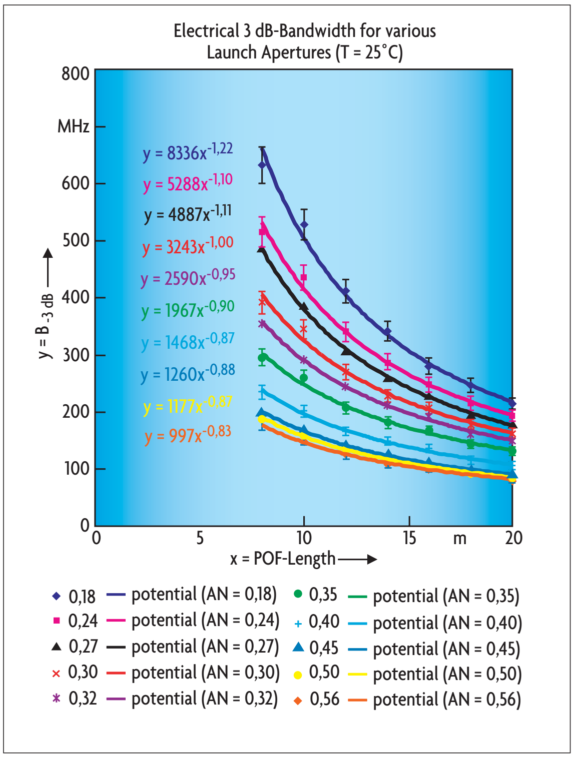
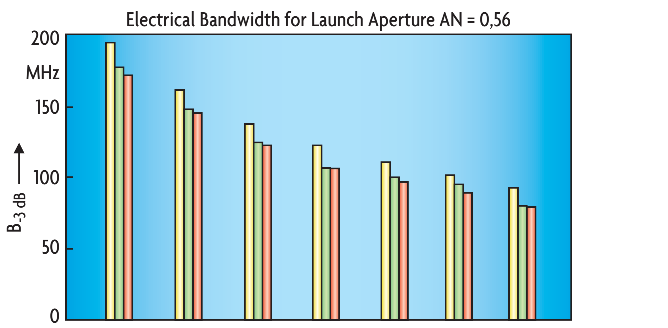


Figure 2. Bandwidth versus POF length, various launch apertures (Mitsubishi Rayon).



Length in m	8	10	12	14	16	18	20	
-40°C	194	161	138	122	111	102	92	MHz
25°C	177	148	124	107	100	94	80	MHz
105°C	172	142	122	107	97	87	79	MHz

Figure 3. Bandwidth dependence on temperature (Mitsubishi Rayon POF).

measurements reveal that the coupling length L_C also depends on the launching condition because the value of q in the exponent increases for decreasing launch aperture. The conclusion is also that the majority of measurements correspond to lengths less than the coupling length of the fiber if q is close to 1.

Influence of temperature

All results of this chapter refer to „Mitsubishi Rayon Heat Resistant" POF. **Figure 3** illustrates the influence of temperature on bandwidth for a launch aperture of 0.56.

In the essence, heating this POF up to 105 °C does not cause an important limitation of transmission bandwidth. The effect of temperature increase to 105 °C is not significant and cooling the fiber to –40 °C again even slightly increases bandwidth.

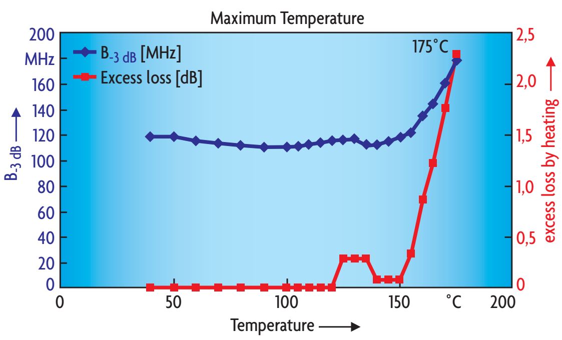
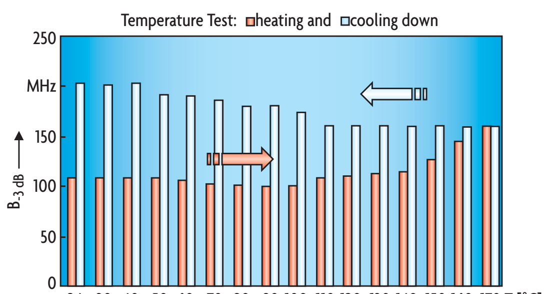


Figure 4. Electrical bandwidth and excess loss versus temperature (Mitsubishi Rayon POF: L = 15 m, launching AN = 0.50).



T [°C]	24	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	
heating	107	107	107	105	104	100	99	98	98	104	108	112	113	123	143	158	MHz
cooling down	201	199	196	190	188	184	179	177	170	159	158	158	158	158	158	158	MHz

Figure 5. Irreversible change due to high temperature exposure; bandwidth versus temperature (Mitsubishi Rayon POF: L = 15 m, launch AN = 0.56).

Figure 4 exposes the temperature limit of 175 °C beyond which the signal transmission will be interrupted. Heating the fiber to 175 °C is accompanied by an excess loss of approximately 2,5 dB above the normal fiber attenuation.

Figure 5 documents a temperature test of a 15 m long fiber heated up to 170 °C (red colored bars) and consecutively cooled down again to 24 °C (blue colored bars). The heating of the fiber above 105 up to 170 °C results in a bandwidth augmentation which remains irreversible if the fiber is cooled down again to room temperature. This goes along with an excess loss of approximately 3.4 dB in addition to the normal fiber attenuation. The fundamental characteristic of the Gaussian shaped transfer function usable for the approximation remains.

A Gaussian characteristic is an easy manageable approximation for the POFs transfer function. For each fiber length L its bandwidth can be determined by a potential function $B_0 \times L^{-q}$ considering that its parameters B_0 and q depend on the launch aperture of the light source. Regarding „Mitsubishi Rayon Heat Resistant" POF environmental temperature within a range of –40 to 105 °C has only a minor effect on transmission bandwidth. Beyond of 105 °C bandwidth increases irreversibly but the excess loss also.

Thus for a given fiber length and launch aperture, realistic analyses can be performed in order to define the limits of performance of the system more clearly. *sj*

Prof. Dr. Jürgen Krapp

achieved the degree of Doctor of Science at the University of Saarland (Germany) in 1986. Since 1994 he teaches at the University of Applied Science in Aalen in the department of Optoelectronics and in the Master Course of Photonics primarily specialising in the field of optical communication systems.

juergen.krapp@htw-aalen.de