Application Note 1

Insights into High-Speed Detectors and High-Frequency Techniques

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Insights into High-Speed Detectors and High-Frequency Techniques

With the advancement of high-transmission-rate systems and short-pulse lasers, many applications now require high time-resolution or equivalently, high frequency-bandwidth optical detection. For example, a high-speed photodetector can measure the frequency and time response of optical systems. This can include measuring the pulses of modelocked laser systems or detecting the data stream of a frequency-multiplexed communication system. A high-speed photodetector will give increased resolution in spectroscopy, including dynamic, pump-probe spectroscopy. Moreover, it can be used in laser heterodyning experiments and for millimeter-wave signal generation. However, even if your optical signal of interest is very fast, if your photodiode or electrical equipment, i.e. oscilloscope or spectrum analyzer, does not have sufficiently large frequency bandwidth, your final measured signal will be as slow as the slowest component of your system. Thus, you require not only a high-speed photodiode which will convert your fast optical signal into a fast electrical signal, but also fast oscilloscopes to observe your waveform, wide bandwidth spectrum analyzers, bias network Ts, connectors and cables. The bandwidth of your optical signal will determine the minimum bandwidth required of all components in your system. This should be your guideline for choosing your measurement equipment.

Estimating the Minimum Frequency Bandwidth

Knowing your frequency requirement is fairly simple if you are making laser heterodyning or optical modulation experiments. Your equipment should have a fairly flat response out to the highest frequency of interest, usually your highest modulation frequency. Oscilloscopes and other time domain equipment most commonly express their frequency bandwidth in terms of a 3-dB bandwidth (the frequency at which the power falls off to 50% of the value at DC). Amplifiers and spectrum analyzers, however, may express their frequency bandwidth in terms of a 1-dB bandwidth (the frequency at which the power falls off to 80% of the value at DC). In either case, to ensure that the equipment will have adequate bandwidth, determine your highest frequency, add a 20% safety margin, and make this your limiting bandwidth for determining your equipment.

For measuring pulses in the time domain, there really is no definite rule for knowing the required frequency bandwidth. Nonetheless, there is a good way to make an estimate. The photodiode converts photons to electrons. It responds to the intensity of the light; thus, if you relate the FWHM (Full-Width at Half Maximum) of the intensity in time to the FWHM of intensity in frequency, you can get some idea of the frequency requirements. For a Gaussian pulse shape with a FWHM of t, the FWHM in frequency is simply 0.44/t for a transform-limited pulse; for a sech^2, it is 0.31/t. Using this as your 3-dB bandwidth gives you a very high value, because the 3-dB point specified for electrical devices is where the power, not the voltage, falls to 50% of its value. Equivalently, this is where the voltage drops to $\sqrt{2}$ of its value. With the photodiode, you are interested in voltage measurements, therefore a more accurate bandwidth is 0.31/t for the Gaussian or 0.22/t for sech^2. For safety, allow 20% more bandwidth, giving approximately 0.37/t and 0.26/t respectively. So on the average, a good rule of thumb is to have a frequency 3-dB bandwidth of 0.4/t where t is the FWHM.

Design Considerations for High-Speed Photodetectors

Modeling the photodiode as an RC circuit is commonly known. There are basically three limiting factors to the speed of a photodetector: diffusion of carriers, drift transit time in the depletion region, and capacitance of the depletion region. The slowest of the three processes is the diffusion of carriers to the highelectric field depletion region from outside that region. To minimize this slow effect, carriers should be generated near or in the depletion region. The second process, transit time, is the time required for the carriers to drift across the depletion region and get swept out of the device. With sufficient reverse bias, these carriers will drift at their saturation velocities, on the order of 3×10^6 cm/s for GaAs. Lastly, the capacitance of the device will determine its RC time constant; R is the load resistance (usually 50 Ω). To maximize a photodiode response, the transit time is typically designed to be comparable to the RC time constant. For instance, given the saturation velocity for GaAs, a 1-ps transit time requires that the depletion layer not be thicker than 0.3 µm. For a comparable RC in a 50-Ω system, the capacitance must be < 20 fF, Since $C = \varepsilon A/d$ (for GaAs $\varepsilon = 13$) where the width, d = 0.3 µm, and A is the area, your active photodiode area must be a maximum of 52.5 µm^2, or a diameter of 8 µm. This simple analysis is similar to how New Focus has designed their photodiodes which are able to achieve 60-GHz bandwidths.

In addition, New Focus has chosen the Schottky configuration over the PIN or APD (avalanche photodiode), The Schottky photodiode is the fastest because of some special characteristics. Its parasitic resistance is lower than in the PIN and APD since the N-type Schottky photodiode has only an N layer and no P layer. Moreover, the diffusion effect is minimized since the carriers are generated primarily at the metal-semiconductor interface, where there exists a high electric field. In an N-type Schottky, the holes, which are the slow carriers, only have to travel a short distance to the metal. The electrons drift at speeds of 3×10^6 cm/s across the depletion layer to the ohmic contact where they are collected. For the PIN, the next fastest of the three configurations, in addition to the transit time across the depletion layer in the high-field intrinsic region, you must consider the time for the carriers to diffuse out of the undepleted regions. The APDs also have fairly long transit times; they must be fairly thick to achieve multiplication.

Electrical Equipment

Cables

Now that you know the minimum frequency bandwidth that is required to maintain the fidelity of your measurement, and you have chosen a photodiode with adequate bandwidth, every electrical component that follows the photodiode must be able to maintain this bandwidth. Let's first start with your cables. Your typical cable around the laboratory is usually RG-58 which is very lossy after 1-2 GHz. Microwave companies have cables that have acceptable losses up to 50 GHz. These cables have an acceptable loss but it is not negligible. Therefore keep all cable lengths to a minimum!

Connectors

The next thing to keep in mind is that all the connectors must also be up to specifications. This includes the bias T which will allow you to bias the photodetector (note: bias Ts are not necessary with New Focus photodetectors). The frequency range of any connector is limited by the occurrence of the first circular waveguide mode in the coaxial structure. Decreasing the diameter of the outer conductor increases the highest usable frequency, while filling the air space with dielectric lowers the highest usable frequency. The BNC (Bayonet Navy) connectors most abundant in the lab are good up to 2 GHz. The SMA (sub-miniature A) connector is good to 24 GHz. The 3.5 mm which uses air as the insulator, can be mated with the SMA and is good up to 34 GHz. The 2.92 mm or Wiltron K connector[1] is good to 40 GHz and is compatible with APC-3.5 and SMA. The 2.4-mm connector is good up to 50 GHz, and the 1.85 mm or the Wiltron V connector is good to 65 GHz. HP makes 3.5 mm, 2.92 mm, 2.4 mm and 1.85 mm as well as the SMA, SMC (to 7 GHz), APC-7 (to 18 GHz) and the Type N 50 Ω (to 18 GHz) connectors.

The performance of all connectors is affected by the quality of the interface for the mated pair. Great care must be taken with these connectors. A torque wrench which is permanently set to the correct torque value should be used to turn the male coupling nut while grasping the body of the connector firmly to keep it from rotating. As the male coupling nut becomes tighter, frictional forces will increase, and the nut and body will tend to lock up, which will cause the body to rotate. This wears away the plating and can score both the outer interface rim and the pin of both connectors. Once a connector has been over-torqued and damaged, it will damage to some extent each connector to which it is mated. This damage lowers its frequency performance. In addition, never hold a male connector coupling nut stationary while screwing the female counterpart into it. This destroys both connectors.

Connector Type	Frequency Range	Compatibility
BNC (Bayonet Navy Connector)	DC - 2 GHz	
SMC (Sub-Miniature C)	DC - 7 GHz	
APC - 7 (Amphenol Precision Connector-7)	DC - 18 GHz	
Type N (Navy) 50 Ω	DC - 18 GHz	
SMA (Sub-Miniature A)	DC - 24 GHz	3.5 mm, 2.92 mm, Wiltron K
3.5 mm	DC - 34 GHz	SMA, 2.92 mm, Wiltron K
2.92 mm or Wiltron K	DC - 40 GHz	SMA, 3.5 mm
2.4 mm	DC - 50 GHz	1.85 mm, Wiltron V
1.85 mm or Wiltron V	DC - 65 GHz	2.4 mm

Instruments (Amplifiers, Oscilloscopes, etc.)

For your electrical instruments, HP and Tektronix[1] manufacture digital oscilloscopes to 50 GHz and spectrum analyzers to 325 GHz. New Focus and other companies have amplifiers to 20 GHz. Remember that the fidelity of your measurement requires that the instrument's response be fairly flat over the frequency bandwidth of interest. This means that both the amplitude response must be flat and the phase response must be linear with frequency. If this is not true of your instrument, for example if your amplifier has a nonlinear phase response, then it will distort your measurement. Your measured signal waveform will become slower.

Summary of Electrical Equipment

Let's now look at three different frequency regimes, <1 GHz, DC to 25 GHz, and DC to 60 GHz. If the maximum frequency of interest is <1 GHz, or the pulse width is >400 ps, APDs may be adequate, and BNC connectors and RG-58 cables certainly are.

For 0-25 GHz or pulse widths >16 ps, PINs or Schottky photodiodes are required as well as SMA connectors and high-performance flexible or semirigid cables. For the bias T, HP makes one good to 26.5 GHz as well as amplifiers good to 26.5 GHz. HP makes a scope good to 34 GHz, and their spectrum analyzers go to 22 GHz or 26.5 GHz. Tektronix also makes a digital oscilloscope good to 20 GHz, and spectrum analyzers good to 33 GHz.

For 0-60 GHz or pulse width >6.7 ps, you must use the highest quality equipment. This includes 1.85-mm or V connectors, ultralow-loss cables, and the best oscilloscopes from HP and Tektronix which both only go to 50 GHz. Wiltron has a bias T for 60-GHz operation. In order to extend to this frequency, the spectrum analyzers must use external mixers. Both HP and Tektronix have this capability.

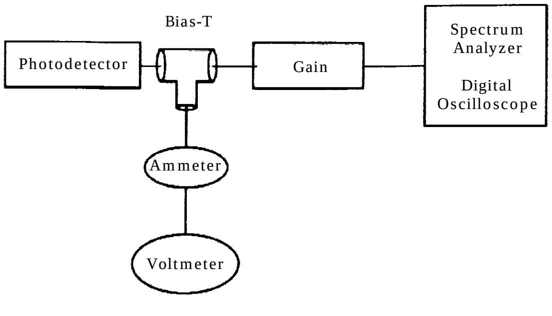

Fig. 1: The experimental measurement system.

Making a Measurement

You are now ready to set up your measurement system. Most setups resemble Fig. 1. First, bias up the photodiode and measure the leakage current. This should not be very large, hopefully only a few µA. Then apply the optical signal. Since the photodetector active area is probably on the order of 10 µm, focus well. Remember that to achieve the best performance all the generated carriers must be in the depletion region. If they are not in this high-field region, then they must diffuse to the depletion region resulting in a slow long tail on your measurement. In communication systems, this can cause higher bit error rates if the tail interferes with the next bit of information. The best way to focus onto the photodetector is to monitor the photocurrent on the ammeter (resolution on the order of 1 µA) and to observe your signal on the spectrum analyzer which is much more sensitive than the digital oscilloscope. If you are observing pulses from a modelocked laser source, you should observe the signal at the repetition rate of your laser. New Focus detectors simplify this process by providing an amplified bias monitor and built-in bias network. Finally, observe your signal on the digital oscilloscope.

The best way to trigger the scope is to use a power splitter to split off some of the signal to the trigger. If there is not enough voltage available, then try triggering off a synthesizer at the same frequency as your laser or signal of interest. However, if you do this you will have to consider that there is timing jitter between your signal and the synthesizer. This will broaden your signal, decreasing its bandwidth. To decrease the amount of timing jitter, trigger off a source that has been phase-locked to whatever is driving your waveform, whether it is your modelocker or another synthesizer.

Actual Pulse Width Measurement

The actual pulse width that you will measure will be a convolution of the optical pulse width, the photodetector impulse response width, all your electrical equipment impulse response widths, and any timing jitter noise. The impulse response width is the width of the output response resulting from an impulse-like (δ-function-like) input. A simple way to estimate the contributions is by using a sum-of-squares technique where the measured pulse width is given by

$$\tau_{\mathrm{measured}} = \sqrt{\tau^2_{\mathrm{optical}} + \tau^2_{\mathrm{photodiode}} + \tau^2_{\mathrm{jitter}} + \tau^2_{\mathrm{electrial}}}$$

τ_{optical} is the optical pulse width; $\tau_{\mathrm{photodiode}}$ is the impulse response of the photodiode (approximately, $0.4/f_{3\text{-dB}}$); τ_{jitter} is the timing jitter, including pulse-to-pulse laser timing fluctuations, synthesizer jitter, etc.; $\tau_{electrical}$ is the impulse response of your electrical equipment. Remember each component contributes by the sum of squares. If your optical signal and your photodiode impulse response are the same, and your jitter and electrical equipment impulse responses are much smaller, your measured signal will be approximately √2 larger than the actual optical signal.

Minimum Signal and Noise

Fig. 2 is a simple block diagram of your photodiode and circuitry (for a good reference see ***Physics of Semiconductor Devices,*** 2nd edition, S.M. Sze[2]). The optical signal and background radiation impinge on the photodiode inducing a current in the external load resistor. If P is your average optical power then I_P, the average photocurrent, is given by

$$I_p = \frac{q\eta P_{opt}}{h\nu}$$

where q is the electron charge, η is the quantum efficiency, and ν is the optical frequency of your light. ($R = \eta\lambda/1.24$, where R is the responsivity, the ratio of photocurrent to the optical power. To convert this to Volts/Watts, simply multiply by the load resistor.) For a 100% sinusoidal modulated signal, the rms optical power is given by $P_{opt}/\sqrt{2}$, and the rms photocurrent, i_p, is

$$i_p = \frac{q\eta P_{opt}}{\sqrt{2}h\nu}$$

Shot noise is noise that is not frequency dependent; it is white noise. In the photodiode case, this random noise, i_s, is caused by current from the background radiation, Ib and that from the dark current, I_d. The dark current is due to thermal generation of electron-hole pairs in the depletion region. The photodiode also has a shot noise from the photocurrent. The total shot noise, that is the meansquared current, is then

$$\langle i^2_s \rangle = 2q(I_p + I_b + I_d)\,B$$

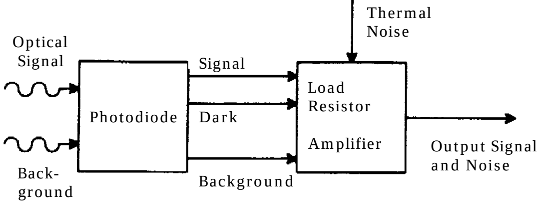

Fig. 2: Photodetection process of a photodiode

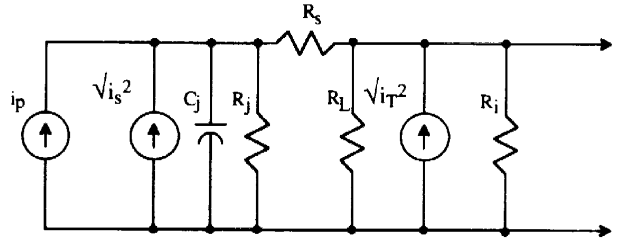

Fig. 3: Equivalent circuit of the photodiode

where B is the bandwidth of your measurement.

The equivalent circuit of the photodiode is shown in Fig. 3. The components i_p, $\sqrt{i^2_s}$, C_j, R_j, and R_s are the rms photocurrent, the shot noise current, the junction capacitance, the junction resistance, and the series resistance. R_L is the external load resistor and R_i is the input resistance of the following amplifier. For the reverse-biased Schottky diode, R_j is very large (> 10^6 Ω) and can be neglected next to R_L which is typically 50-500 Ω. The series-connected R_s is usually much smaller than the other resistances and can be neglected as well. The thermal Johnson noise is then given by

$$\langle i^2_T \rangle = 4kT(1/R_L)B + \langle i_i^2 \rangle$$

Since the amplifier input resistance may or may not be due to an actual resistor, the noise current due to R_i is listed separately as i_i.

With the above information, we can then find the power signal-to-noise ratio which can be expressed as

$$(S/N)_{power} = \frac{i^2_p R_{eq}}{(\langle i^2_s \rangle + \langle i^2_T \rangle)\,R_{eq}}$$
$$= \frac{\frac{1}{2}(q\eta P_{opt}/h\nu)^2}{2q(I_p + I_b + I_d)B + 4kTB/R_L + \langle i_i^2 \rangle}$$

where $1/R_{eq} = (1/R_L) + (1/R_i)$.

Thus to achieve a certain signal-to-noise ratio, the minimum optical power required is

$$(P_{opt})_{min} = \frac{2h\nu B}{\eta}\left(\frac{S}{N}\right)\left\{1 + \left[\frac{I_{eq}}{qB(S/N)}\right]^{1/2}\right\}$$

where $I_{eq} = I_b + I_d + 2kT/qR_{eq} + \langle i_i^2 \rangle/2qB$. If we were to look at an example, where $I_b = I_d = 1$ μA, $i_i \approx 0$, and $R_L = 50$ Ω, then we would find that in the expression for I_{eq}, the Johnson noise term dominates and $I_{eq} = 1$ mA.

Let's now look at two limits, one where $I_{eq}/qB(S/N)$ is much less than unity, and the other where this is much larger than unity. If $I_{eq}/qB(S/N)$

is much less than unity, the dark current, background current and thermal Johnson noise are very small. In this case the minimum optical power is determined by the quantum noise associated with the optical signal. However, this case is very difficult to achieve; in our above example, B(S/N) must be much greater than 6.25 x 10^{15} Hz. In the other limit, the background radiation and/or thermal noise of the equivalent resistor dominates. Then the minimum optical power is

$$(P_{opt})_{min} = \frac{2h\nu}{\eta}\left(\frac{BI_{eq}}{q}\right)^{1/2}\left(\frac{S}{N}\right)^{1/2}$$

To increase the sensitivity of the photodiode, one would want to increase the quantum efficiency, or increase the equivalent resistor. The noise-equivalent-power, or the optical power required to have S/N = 1 (the optical signal is exactly equal to the output noise) over a 1-Hz bandwidth is simply

$$NEP = \sqrt{2}(h\nu/\eta)(I_{eq}/q)^{1/2} \qquad W/Hz^{1/2}$$

Now to consider the New Focus 1000 Series photodiodes, let $\langle i_i^2 \rangle = 0$ since there is no internal amplification and the external amplifier selected will vary. In this case, thermal noise from the load resistor is the dominant source of noise. Thus, $I_{eq} = 2kT/qR_{eq}$, and the minimum optical power can be rewritten as

$$(P_{opt})_{min} = \frac{2h\nu}{\eta}\left(\frac{2kTB}{q^2R_L}\right)^{1/2}\left(\frac{S}{N}\right)^{1/2} = \frac{\sqrt{2}h\nu i_T}{\eta\ q}\left(\frac{S}{N}\right)^{1/2}$$
$$= \frac{\sqrt{2}i_TR_{eq}}{R}\left(\frac{S}{N}\right)^{1/2} \approx \frac{i_TR_{eq}}{R}\left(\frac{S}{N}\right)^{1/2}$$

R is the responsivity in mV/mW. By setting S = N or where the optical signal is equal to the output noise, we can find the weakest optical signal that could possibly be measured. For example, the internal load resistor for the Model 1001 is 100 Ω, and 50 Ω for the other photodiodes. Using this to calculate the noise current, we find for the 1001, $i_T/\sqrt{B}$ is 13 pA√Hz, and for the Models 1002, 1011, and 1014, it is 18 pA√Hz. With the photodiode connected to a 50-Ω system (R_i = 50 Ω), Req = 33 Ω for the 1001, and 25 Ω for the others. Calculating the minimum optical power (λ = 0.532 µm) for a S/N = 1 and a bandwidth of 1 Hz, you will find that for the 1001, the minimum optical power is 60 pW, and for the 1002, it is 90 pW. For the 101X Series, at 1.3 µm, the minimum optical power is 41 pW. A 1-Hz bandwidth implies an integration time of roughly 1s. This is the minimum detectable optical power if all the following equipment were to add no noise. In reality, your electrical equipment will most likely have much worse noise performance; it will not be able to detect 3 nV. Then the worst component will determine your minimum detectable signal. For example, if your oscilloscope is the culprit, the minimum detectable signal will be dominated by its minimum sensitivity of about 1 mV. If your responsivity is 5 mV/mW for 0.532-µm light, as it is for the New Focus Model 1002, then the minimum detectable peak power is 200 µW.

It is interesting to note that given a photodiode capacitance of 50 fF as in the Model 1002, you would expect to generate a voltage of 3 µV for a single photon, thus raising the possibility of photon counting on a very short time scale. However, the rms noise voltage for R_L = 50 Ω is 220 µV in a 60-GHz bandwidth. Therefore, detecting a single photon is not possible. For a signal-to-noise ratio of unity, the capacitance would have to be lowered to an amazing 9 x 10^{-18} F.

Frequency Response Considerations

Finally, let's discuss how various frequency responses will affect your time domain results. Optimally, you would like a flat response out to your frequency of interest. New Focus' photodiodes have been individually measured from DC to 60 GHz, and they have a fairly flat response to 60 GHz. Beyond 60 GHz, the responsivity of the diode drops sharply. This is due to the RC pole from the diode in conjunction with other poles from parasitics.

On the other side of the spectrum, it is also important to have a flat response to DC. If there is no response at DC, you are essentially AC coupled and will not be able to measure any DC level. There will be no way to ensure that your modulation depth is complete, and long pulses will be severely distorted. If, on the other hand, the response is peaked at DC, there will be artificially long tails on pulse measurements in the time domain. One possible cause may be that the

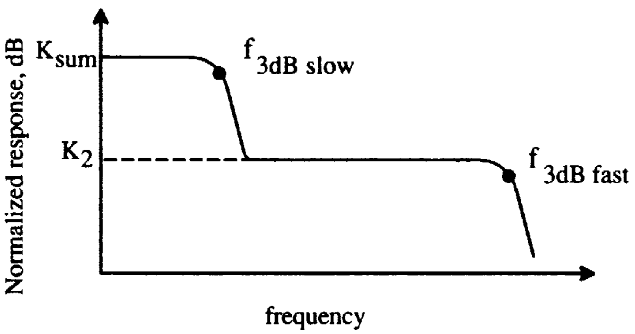

Fig. 4: Frequency response that is peaked at DC. $f_{3dB\ slow}$ is the point that is 3 dB down from K_{sum}; $f_{3dB\ fast}$ is that point that is 3dB down from K_2.

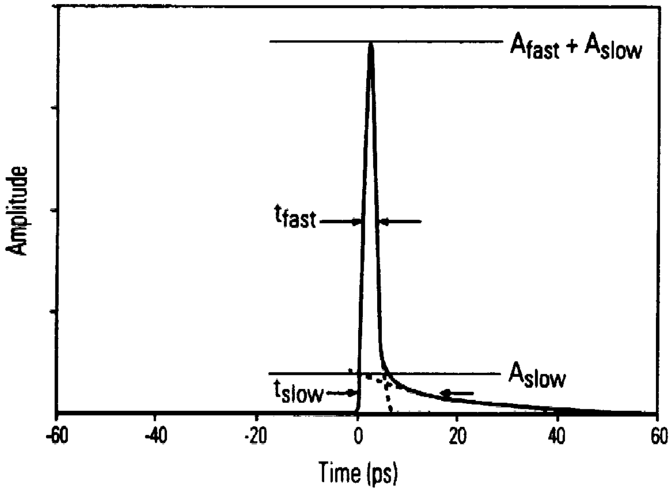

Fig. 5: The pulse shown in Fig. 5 can be modeled as the sum of two pulses, one fast and the other slow. A_{fast} and t_{fast} are the amplitude and FWHM of the fast pulse. A_{slow} and t_{slow} are the amplitude and FWHM of the slow pulse

photodiode is limited by the diffusion effect, possibly from poor focusing. The carriers have been generated outside the active area of your diode. If however, you find that your frequency response is peaked at DC as in Fig. 4, and this is not due to a focusing problem, there is an easy way to estimate how this affects your measurement.

Remember that the Fourier transform of your waveform from the time domain to the frequency domain will result in your frequency response. Moreover, since Fourier analysis is completely linear, you can model a waveform as the sum of fast and slow components. For example, the pulse shown in Fig. 5 has an artificially long tail. It can be modeled as the sum of a fast pulse and a slow pulse. Let's say that t_{fast} and A_{fast} are the FWHM and amplitude of the fast component, and t_{slow} and A_{slow} for the slow component. If your curve resembles Fig. 4, first find the 3-dB point of the slow, the lower frequency, and then the 3dB point of the fast, the higher frequency. From these, you should be able to find tslow and tfast since they are related by t = 0.4/f. Then we know that the DC or 0 frequency response is the area under your curve in time. For example, for a Gaussian, the amplitude at DC is related to the pulse width and amplitude in the time domain. The wider the pulse width or the greater the amplitude, the higher the DC response. Thus, K_1 is proportional to $A_{slow}\ t_{slow}$ while K_2 is proportional to $A_{fast}\ t_{fast}$. In Fig. 4, $K_{sum} = K_1 + K_2$. Now, normalize both in the time and frequency domain to the the fast pulse. So now, A'_{slow} is that normalized to A_{fast}, and K'_{sum} is that normalized to K_2. This implies that $K'_{Sum} \approx 1 + A'_{Slow}\ t_{slow}/t_{fast} = 1 + A'_{slow}\ f_{fast}/f_{slow}$. Therefore,

$$A'_{slow} \approx \frac{(K'_{sum} - 1) f_{slow}}{f_{fast}}$$

Once you know the amplitudes, and FWHM, simply sum the two components to get some idea of what your waveform will look like in the time domain.

Lastly, the measured frequency response will give you a good relative measurement from DC to 60 GHz. However, if you wish to make an accurate absolute measurement it is very difficult. This is because you must consider the responses of all your cables, connectors, and equipment. If just one of those is not correct, you will have an error in your measurement. It is necessary to do what New Focus has done with its photodiode and measure the frequency response of each and every component. This can be done quite easily with the aid of an automatic network analyzer but is quite tedious without it.

Summary

High-speed optical measurements not only require the generation of fast optical signals, but also the detection of them. In choosing your photodiode and all your electrical equipment, including cables and connectors, keep in mind the frequency response required to maintain fidelity of your signal. Remember that your measurement will be as slow as the slowest component of your system!

References

1. For technical assistance, suggestions for equipment selection, and additional references, contact New Focus at 415-961-2108.
2. Sze, S.M., ***Physics of Semiconductor Devices,*** 2nd ed., John Wiley and Sons, New York, 1981.

Author

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