LOGARITHMIC PROCESSING APPLIED TO NETWORK POWER MONITORING

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Optical power monitoring is a necessary ingredient to any successful DWDM optical network. As network designers continue to decrease channel spacing in an effort to expand bandwidth capacity, accurate power monitoring is necessary to ensure all system components are in compliance. Power levels may need to be accurately monitored to maintain a predetermined quality of service. And for long haul systems, intermediate power monitoring is required to ensure optical transmission characteristics satisfy system requirements. Any location in the optical path where a network element exists, such as optical amplifiers, switch fabric, filters, couplers, and spectral monitoring test equipment, may warrant monitoring. Logarithmic processing of the received signal can simplify the power measurement dilemma.

Previous techniques for determining optical power have utilized trans-impedance amplifiers (TIAs), followed by low-pass filter stages, needed to sample the average value at a wavelength of interest. When a decibel (dB) equivalent is desired, it is necessary to utilize look-up tables or numerical calculation of the base-10 logarithm of the signal. Due to the linear nature of this optical-to-electrical conversion, such systems tend to require high-resolution analog to digital converters (ADCs) and processors capable of high precision calculations in order to maintain acceptable measurement accuracy over a wide dynamic range. Increased supply voltages may also be needed for the front-end TIA stage to avoid clipping of the amplified signal. These various factors often result in rather expensive complicated solutions.

The Logarithmic Transformation

A more powerful alternative is the use of logarithmic processing in the analog domain. With this approach a wide dynamic range can be compressed and simultaneously transformed to a decibel representation. This allows the use of a *low*-resolution ADC, and provides a more useful output metric for determining the average power level of an incident signal in a dBm fashion.

There are several architectures used to derive logarithmic transformations in the analog domain. The most common available in an integrated form use progressive-compression/successive-detection. Using a cascade of fixed gain amplifiers tapped in a successive manner by several detector cells, an input signal is progressively compressed as it propagates through the series of amplifiers. The outputs of the detectors are summed together to provide a signal that is proportional to the logarithm of the input. The integrating properties of the detector cells results in the logarithm of the average value of input signal. This style of log amplifier is commonly referred to as demodulating because of its ability to directly reveal the envelope of an amplitude-modulated signal. Unfortunately these devices tend to provide voltage mode inputs and are inappropriate for direct interfacing to a photodiode. A more historical implementation utilizes the inherent natural logarithmic relationship between the collector current in a bipolar transistor junction and the resulting base to emitter voltage. Logarithmic amplifiers that take advantage of the log-exponential properties of a junction are known as translinear log amps.

Many ambitious analog designers have had limited success discretely implementing current-mode translinear log amplifier circuits. These designs usually include matched transistor pairs to provide good thermal tracking and conformance, as well as exotic high-temperature coefficient resistors used to cancel out additional temperature dependencies inherent to the transistor junction. Recent advances in monolithic circuit design now permit the successful integration of translinear circuits used to perform a true logarithmic transformation, allowing a direct conversion of a photocurrent to a decibel related voltage.

The temperature compensation problem associated with a discrete translinear design can be essentially eliminated using integrated temperature correction techniques. These new devices allow for simplified procedures to accurately determine absolute power levels.

There are a growing number of integrated translinear log-amps becoming available to the market. One example, the AD8304 from Analog Devices Inc., is a new translinear logarithmic amplifier/converter designed by the world-renowned Dr. Barrie Gilbert; innovator of the *Gilbert Cell*, *X-Amp™*, and several other patented analog signal processing designs. The device is specifically designed for photodiode power measurement applications. The added flexibility of controlled adjustment of the current summing node potential and an onboard un-dedicated buffer amplifier, allows for a variety of non-optical applications including logarithmic signal compression, closed loop precision current sourcing, and several other applications.

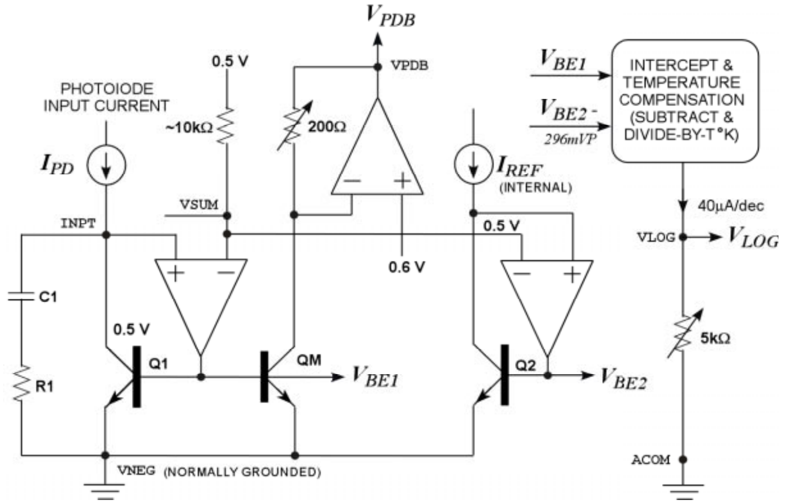


Figure 1. Simplified Schematic

A translinear[1] logarithmic amplifier takes advantage of the inherent logarithmic relationship between the collector current of a transistor and the resulting base-to-emitter voltage. The basic circuit functions for a single supply solution are illustrated in Figure 1. The input signal current flows into the NPN logging transistor Q1, producing a bias voltage $V_{BE1} = V_T \log(I_{PD}/I_S)$. Q2 generates a second bias voltage V_{BE2} using a temperature-stable internal reference current I_{REF}. The highly temperature dependent saturation current I_S is conveniently canceled when transistors Q1 and Q2 are closely matched. The difference of the signals is taken to produce a voltage equal to:

$$V_{BE1} - V_{BE2} = V_T \cdot \log_{10}(\tfrac{I_{PD}}{Is}) - V_T \cdot \log_{10}(\tfrac{I_{REF}}{Is}) = V_T \cdot \log_{10}(\tfrac{I_{PD}}{I_{REF}}) \quad (1)$$

The temperature dependent term $V_T = kT/q$ is corrected and re-scaled using proprietary design techniques to provide a final output signal at the **VLOG** pin:

$$V_{LOG} = V_Y \cdot \log_{10}(\tfrac{I_{PD}}{I_Z}) \quad (2)$$

where

V_Y is the logarithmic slope equal to 200 mV/decade
I_Z is the logarithmic intercept equal to 100pA**.**

[1] For a basic discussion of the topic see "Translinear Circuits: An Historical Overview", B. Gilbert, *Analog Integrated Circuits and Signal Processing*, 9, pp 95-118, 1996

Logarithmic signal processing allows for a linear-in-dB transfer function that can be accurately modeled using a simple straight-line linear regression. In general, a logarithmic detector provides an output signal that is proportional to the logarithm of an input stimulus. In the case of optical power monitoring, the stimulus is a photocurrent generated by a photodiode with a given responsivity ρ, in units of Amps/Watt. Using equation 2, the linear-in-dB output voltage can be expressed as:

$$V_{LOG} = 200mV/decade \cdot \log_{10}\left(\frac{I_{PD}/\rho}{I_Z/\rho}\right)$$

or

$$V_{LOG} = 200mV/decade \cdot \log_{10}\left(\frac{P_{IN}}{P_Z}\right) \tag{3}$$

Since a photodiode generates a current that is directly proportional to the incident optical flux, every 10 dB change in optical power results in a decade change in photo-current. This relationship allows us to express the logarithmic slope in units of mVolts-per-dB and rewrite the equation for the logarithmic output voltage as:

$$V_{LOG} = 20mV/dB \cdot [P_{IN}(dBm) - P_Z(dBm)] \tag{4}$$

where $P_{IN}(dBm) = 10 \cdot \log_{10}\left(\frac{P_{IN}(mW)}{1mW}\right)$ and $P_Z(dBm) = 10 \cdot \log_{10}\left(\frac{I_Z}{\rho}\right) + 30dBm$.

Biasing Considerations

Typically designers are accustomed to applying a fixed reverse bias across a photodiode, or in faint level detection applications, no bias whatsoever. The choice of whether to reverse bias or not is dependent on the photodiode characteristics and the intended dynamic range. For faint level applications, zero bias is applied resulting in a photovoltaic mode of operation where the dark current is essentially zero. This provides the best sensitivity for an uncooled detector, though the linearity of the photodiode degrades for larger signal inputs. At strong optical input levels the internal series resistance of the photodiode can result in a net forward voltage to develop across the detector junction. This forward voltage will result in a reduction of the depletion layer and cause the responsivity to decrease for increasing incident flux. This situation is avoided by simply using a large enough reverse bias to ensure that the electron-holes pairs are sufficiently depleted.

To achieve wide dynamic range performance it is desirable to operate the photodiode with essentially zero bias applied at low signal levels, and a moderately strong reverse bias at large signal levels. This can be accomplished by using a linear replica of the photocurrent to generate a voltage that is then used to reverse bias the photodiode. Transistor QM in Figure 1 is used to mirror the input current. The mirrored current is then applied to an I-to-V stage with a fixed trans-resistance of 200 mV/mA. The resulting voltage can then be used to drive the cathode of the photodiode. Using a fixed anode potential, this results in a linearly increasing net reverse bias across the photodiode junction with increasing input optical power. The adaptively changing bias allows the photodiode to operate in a photovoltaic mode at faint levels, and gradually transition to a photoconductive mode for increasing input signal levels. This form of adaptive biasing is necessary for wide dynamic range applications where good linearity is required over several decades of input optical power.

Calibration

Linear techniques using TIAs provide a linear transfer function that requires multipoint calibration in order to achieve acceptable accuracy. Optical coupling uncertainty, along with variations in photodiode responsivity, may cause the transfer function to slide to the left or right as indicated in Figure 2. The transverse slide of the transfer function can generate gross errors if left uncalibrated. As a result, it is necessary to generate a calibrated look-up table in order to accurately estimate an input optical power level based upon a sampled digital value.

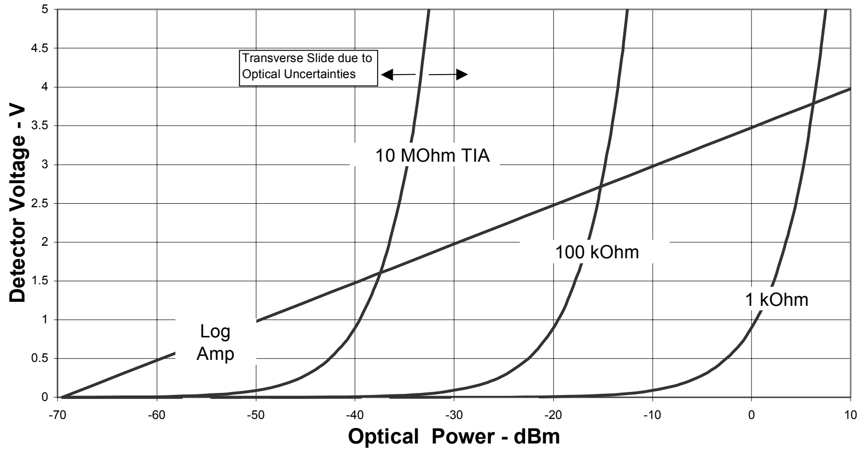
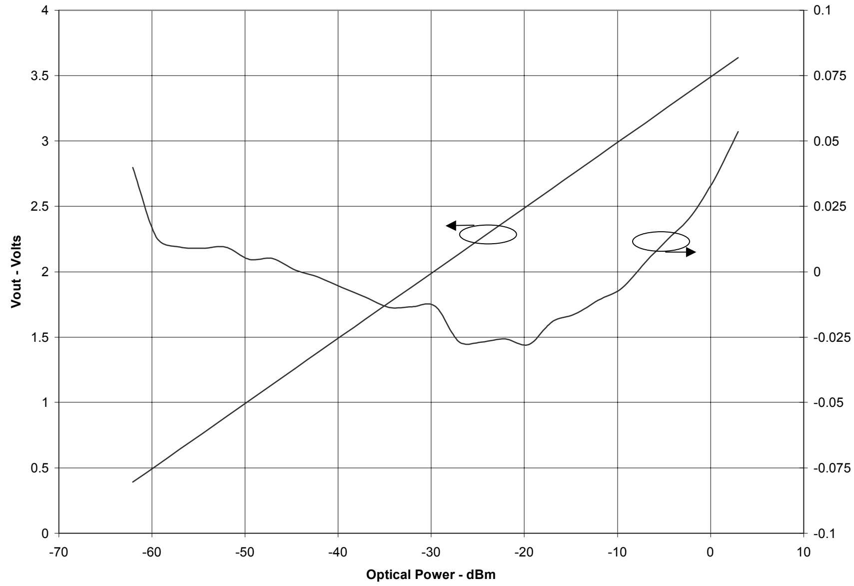


Figure 2. Transfer Function of Transimpedance (TIA) Amplifier versus Log Amp. Coupling uncertainty, responsivity deviations and fiber loss can cause a transverse slide of the transfer function often requiring multi-point calibration.

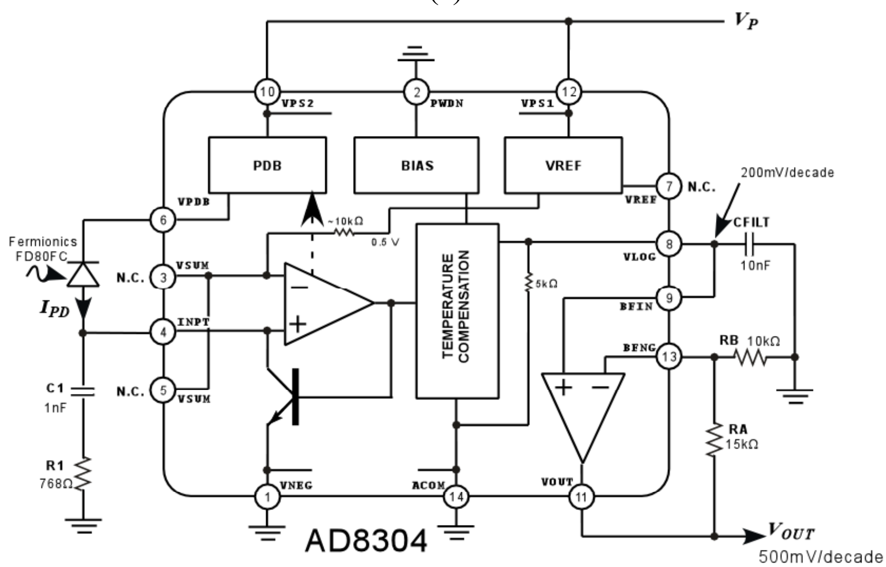
The plot in Figure 2 displays the dynamic range limitations of a classical trans-impedance amplifier used to amplify the photo-current of typical telecom grade photodiode. For an output voltage swing of 5 V the TIA offers less than 30 decibels of optical dynamic range. Additionally, any coupling uncertainty or responsivity variations will cause a transverse slide of the transfer function. On the same plot, the transfer function of a logarithmic amplifier is displayed for comparison. The same uncertainties result in a fixed intercept offset that can easily be removed using a single point calibration when using logarithmic conversion. For the same 5 V output voltage swing, a 100 pA intercept, and a final logarithmic slope of 500 mV/decade, the log amp provides 80 decibels of optical dynamic range with a constant volt-per-dB relationship. The clear advantage of increased dynamic range and a constant volts-per-dB slope makes the log amp front end a superior method of conditioning the signal prior to analog to digital conversion.

Performance

Figure 3 demonstrates the ease of implementation and high performance measurement capability of the AD8304 Logarithmic Detector. In this example, the adaptive photodiode biaser feature is used to control the reverse bias across the photodiode. The photodiode is essentially zero-biased for faint optical signal levels, i.e., photovoltaic mode, and then the reverse bias gradually increases in a linear manner with increasing signal levels to provide photoconductive mode of operation at the high-end of the dynamic range. This allows the photodiode to perform in a linear manner over the entire input range.



(a)



(b)

Fig. 3. Log Transfer Function and Circuit Representation

Using a stable 1.5 µm laser source in conjunction with an optical variable attenuator and field strength meter, optical power levels were swept from –64 dBm to +3 dBm. A Fermionics InGaAs p-i-n photodiode with a responsivity of 0.9 A/W was used as the photo-detector. The resulting photo-current varied from 360 pA to 2 mA. The buffer amplifier was configured for a voltage gain of 2.5×, this results in a final logarithmic slope of 500 mV/decade or 50 mV/dB. The equation describing the logarithmic transfer function can be expressed as

$$V_{OUT} = 2.5 \times 20mV/dB \cdot [P_{IN}(dBm) - (10 \cdot \log_{10}(100pA/0.9A/W) + 30dBm)]$$

or

$$V_{OUT} = 50mV/dB \cdot [P_{IN}(dBm) + 69.5dBm] \quad (5)$$

Equation 5 was then used to assess the accuracy or conformance of the log transformation. The error was defined as the difference of the measured voltage and the value predicted from equation 5, the final result was then expressed in units of dB. The logarithmic conformance remained within a ± 0.1 dB over almost a seven-decade optical dynamic range.

Applications

Several examples of optical power monitoring applications using translinear log amps are presented in Figure 4. A pair of log amps are used to measure the gain of an optical amplifier in Figure 4a. Since the outputs are proportional to the decibel value of the input and output power, the gain in dB can be easily computed by taking the difference of the log voltages.

$$V_{LOG2} - V_{LOG1} = V_{Y2} \cdot (P_2 - P_{Z2}) - V_{Y1} \cdot (P_1 - P_{Z1}) \tag{6}$$

where P_1 is the power in dBm of the input tap

P_2 is the power in dBm of the output tap

P_{Z1} and P_{Z2} are the corresponding intercepts for each log amp expressed as an equivalent optical power in unit of dBm

V_{Y1} and V_{Y2} are the corresponding slopes for each log amp expressed in units of Volts per dB.

Since the logarithmic slope and intercept of the individual log amps are laser trimmed to equal values, i.e., $V_{Y1} = V_{Y2}$ and $P_{z1} = P_{Z2}$, then the gain can be calculated as

$$Gain(dB) = P_2 - P_1 = \frac{V_{LOG2} - V_{LOG1}}{V_Y} \tag{7}$$

A similar application is indicted in Figure 4b where a pair of log amps are used to measure the attenuation of a variable optical attenuator (VOA).

Figure 4c is an example of an optical switch matrix where a MEMs (micro electro-mechanical) mirror array is used to reflect incoming light to the desired exiting fiber. Optical power monitoring of each input and output fiber is necessary to ensure light is efficiently re-directed to the intended port. In this example, it is desirable to measure the transmission or absorption through the switch matrix. The log amplifier is necessary to cope with the wide dynamic range of signal levels and to provide a simplified calculation of the transmission loss on each channel. Similar to the previous calculations, the transmission or absorption can be readily measured using the difference of the log voltages.

A common architecture used to design tunable wavelength laser diodes is depicted in Figure 4d. The emission wavelength of the laser diode is influenced by a thermo-electric cooler (TEC) as well as the drive current. Here a set of log amps are used to measure the percentage of transmitted light through a long-pass optical filter. The emission wavelength can then be predicted if the stop-band to pass-band transition of the filter is well defined. The TEC controller and laser diode driver are then adjusted to provide the desired output wavelength and power level.

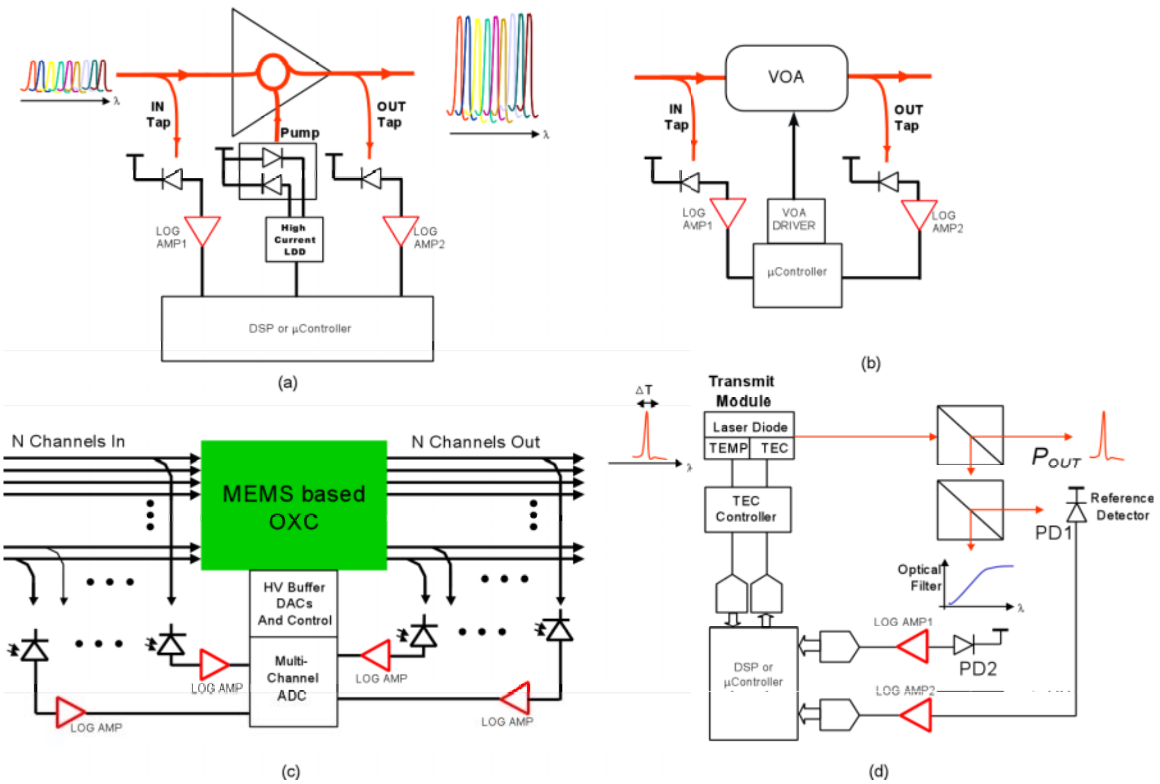


Figure 4. Several Log Amp Optical Power Monitoring Applications. a) An Optical Amplifier Gain Measurement, b) VOA Attenuation Measurement, c) MEMS Optical Cross Connect Application, d) Tunable Laser Application.