All Optical Wideband Microwave Noise Filter

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Abstract

A novel configuration of fiber-optic link is demonstrated which forms a passive microwave noise reduction filter. This circuit is designed to suppress unwanted RF amplitude noise arising from either the transmission laser due to relative intensity noise (RIN), or from an optical amplifier in the form of amplified spontaneous emission (ASE). The optics can be configured to select the center RF frequency of the noise filter as well as the depth and bandwidth for filtering.

I. Introduction

Transmitting analog microwave signals via fiber-optic links is an enabling technology for signal processing, antenna remoting, and telecommunications applications such as cable television transmission or hybrid fiber wireless systems. Due to the wide dynamic-range and signal complexity associated with modern high performance transmit/receive systems, the characteristic performance of these photonic links is limited by the noise figure (NF) of the optical system. One challenging component to optimize in these systems is the optical transmitter since it must have a linear response while providing high average power with low noise [1].

Since optical transmitters propagate signal as well as phase and intensity noise, minimizing the optical noise has long been a goal. To this end, many noise reduction techniques for optical links have been examined and have taken many forms including, but not limited to: actively feeding back on the output intensity of a laser by electro-optic [2] or electronic [3] means to reduce noise, here the noise reduction is usually bandwidth limited. Differential detection techniques to improve the overall link performance [4, 5]. The use of narrow tunable filters to reduce the bandwidth of the optical amplifier noise [6]. Lastly, there are noise filters employing unbalanced interferometers either as the primary noise reduction filter [7] or as part of a heterodyne technique designed to improve the noise figure of the transmitted signal [8]. One limitation of many of the above noise reduction techniques is that while the optical noise is reduced, so is the transmitted bandwidth. To address these issues, we present a method which reduces the optical intensity noise in a photonic link while maintaining wideband transmission capability.

II. System Design

A schematic diagram illustrating the experimental configuration used to demonstrate our wide bandwidth optical filter is shown in Fig. 1. A laser generates an optical signal whose power is amplified by an erbium doped fiber amplifier (EDFA). The output of the EDFA is fed into two optical notch filters connected in series, whose output is then detected by a RF photodiode.

The fundamental optical element in our wideband noise filter is an unbalanced fiber-optic (FO) Mach-Zender Interferometer (MZI). The boxed sections of Fig. 1 show a schematic diagram of two MZI in series. For each filter, a polarization maintaining (PM) 50/50% FO coupler divides light into two equal parts which travel through two separate lengths of PM optical fiber. The light is then recombined by a second PM 50/50% coupler. When light is recombined within the second FO coupler, optical interference results due to the coherent nature of laser light and the fact that the light has remained polarized within the interferometer. The intensity of the coherent light at port 1 (I₁) and port 2 (I₂) is given by...
Fig. 1 Schematic diagram of a widebandwidth nulling filter system. Within the box are two unbalanced MZI set at two different frequencies, which make up the noise filter.

\[ I_1 = I_0 \cos^2(\pi \Delta L nf/c) \]
\[ I_2 = I_0 \cos^2(\pi \Delta L nf/c + \pi/2) \]

where \( I_0 \) is the input optical intensity, \( \Delta L \) is the net optical path length difference, \( c/n \) is the speed of light in optical fiber, and \( f \) is the frequency spacing of the interference fringes. Note that when the length of the two arms of the MZI are exactly equal \( \Delta L = 0 \), the coherent light will add constructively at port 1 and destructively at port 2 \( [\cos(0) = 1; \cos(\pi/2) = 0] \). If the path length difference between the two optical arms of the interferometer is a multiple of half of an optical wavelength, \( m(\lambda/2) = c/(2nf) \), the coherent light output will oscillate between constructive and/or destructive interference at ports 1 and 2 [9].

Since the optical path length difference in the interferometer, controls the balance of optical power at the output ports, an optical nulling filter can be produced by selecting \( \Delta L = c/(2nf) \), where \( f \) is the frequency to be filtered. In this case, the argument of the cosine is equated to \( \pi/2 \), which returns a zero. This null condition means no optical intensity passes through port 1. If only the port 1 optical intensity is passed further through the system, then a notch filter which reduces the optical noise at a specific microwave frequency is produced. With this type of filter, the higher order odd harmonics, of the desired frequency, will also produce the null condition, since odd multiples of the filter frequency also meet the nulling condition.

A broad band noise filter can be produced by linking several single notch filters in series. By designing the filters such that the nulls of early filters are at the peaks of subsequent filters, broadband nulling can be produced. The two filters in our demonstration have their path length differences designed such that the filtering frequency of MZI 1 is half the filtering frequency of MZI 2. That is, \( 2f_1 = f_2 \). After filtering, the resultant output from is then passed onto the rest of the optical system.

For this demonstration, the path length differences for the filters were designed such that the filtered frequencies were expected to be at 7.5 GHz and 15.0 GHz. The demonstrated filters also include piezo-electric line stretchers, used to fine tune the overall optical path difference between the arms of the interferometers, insuring a null condition at the frequency of interest.

III. Results and Discussion

To experimentally verify the functionality of the coherent optical microwave filter, the null frequencies of the filters were measured. An optical intensity modulator was inserted between the laser/EDFA optical source and the optical MZI filters. The output of the optical filters was then connected to an optical RF photodiode. With induced RF modulation on the optical carrier, nulls from the optical filters were measured on an RF network analyzer at 7.75 GHz and 14.8 GHz for filter 1 and filter 2, respectively, very close to our original design goals. In addition the insertion loss of the filters were measured to be <0.5 dB per filter.

Once the nulling ability of the optical filters was verified, the optical filters were connected directly to a laser/EDFA optical source, and the optical output of the filters...
was measured with an RF photodiode. The photodiode's microwave output was amplified and measured by an RF spectrum analyzer. Figure 2 shows the measured output from an optical link without any filtering (solid line) and with the 7.75 GHz optical RF filter in line (dot symbols). A significant reduction in the noise is clear, with the nulls of the filter approaching the shot noise limit of the detector (-168 dBm/Hz).

To highlight the action of the optical RF filter, the difference between the two curves from Fig. 2 is shown in Fig. 3 (dot symbols). A theoretical curve (solid line) is also shown. Figure 4 shows the difference between the non-filtered optical output and that from the 14.8 GHz filter (dot symbols). A theoretical curve (solid line) is also shown for this filter. Note that Figs. 3 and 4 show that both the 7.75 and 14.8 GHz filters are able to reduce the optical noise, at the as built frequencies and their odd harmonics, by greater than 10 dB.

By linking the two filters in series, a combined wide bandwidth filter is expected. The result of combining the two filters in series, is shown in Fig. 5. The symbols show the difference between the unfiltered optical power and the optical power after passing the light through both optical filters. A theoretical curve (solid line) is also shown. A 10 dB reduction in the noise level from 6 to 24 GHz is observed for this filtering arrangement. A slight asymmetry in the resultant rejected fil-

Fig 2. Measured noise power with (dots) and without (solid) for the 7.75 GHz filter.

Fig 3. Measured noise reduction for the 7.75 GHz filter. The line is a theoretical fit.

Fig 4. Measured noise reduction for the 14.8 GHz filter. The line is a theoretical fit.

Fig 5. Measured noise reduction for the combination of the 7.75 GHz filter and the 14.8 GHz filter, linked in series. Solid line is a theoretical fit.
tered RF band is observed in these plots, which is the result of the fact that the center frequency of filter 1 is not at exactly half that of filter 2. Despite this minor problem, a wide-bandwidth microwave filter has been produced with this simple optical filtering arrangement.

IV Conclusions

We have produced an all optical wide-band RF filter designed to null laser RIN and amplifier ASE noise. For a single pole filter, the filters were able to reduce noise levels by 10 dB at the center frequency. When coupled together in series, the combined filter achieved a 10 dB reduction in the noise levels over an 18 GHz bandwidth, with minimal insertion loss. Expanding the filtering bandwidth can be achieved by incorporating more filters at harmonic frequencies. The depth of the filter nulls can also be controlled by increasing the number of filters at any given frequency.

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References