Optical Domain Demultiplexing of Subcarrier Multiplexed Cellular and Wireless LAN Radio Signals

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ABSTRACT
Subcarrier multiplexed transmission of cellular (900 MHz), personal communications systems (1.8 GHz) and wireless LAN (2.4 GHz) over the fiber has interesting applications. These multi channel radio over fiber links can connect enhanced wireless hot-spots that will support high speed wireless LAN services or low speed cellular services to different customers from the same antenna. Optical pre-filtering of SCM signals allows the use of inexpensive photodetector and increases network flexibility with fiber based optical filters. However, realizing optical demultiplexing at such low frequencies necessitates optical filters with high selectivity and low insertion loss. In this paper, we implemented a fiber wireless access system, where demultiplexing of subcarrier multiplexed cellular and WLAN signals was demonstrated in optical domain using a sub-picometer bandpass filter. Our novel fiber Bragg grating based bandpass filter has a bandwidth of 120 MHz at -3dB, 360 MHz at -10 dB and 1.5 GHz at -20 dB respectively. We experimentally verified that this filter could adequately isolate signals at as low as 900 MHz from 2.4 GHz. Experimental results show that the designed all optical demultiplexer provides about 25 dB isolation between 900 MHz and 2.4 GHz radio signals.

Keywords: Radio over fiber, microwave fiber-optics, subcarrier multiplexing, sub-picometer bandpass filter, fiber Bragg grating, optical demultiplexing, fiber-wireless systems, wireless hot spots, antenna remoting

1. INTRODUCTION
Current wireless communication systems are challenged with the demand for high capacity with the rapidly growing interest to provide multimedia services, where variety of medias such as voice, data and video are integrated. Fiber wireless (Fi-Wi) access schemes, in conjunction with subcarrier multiplexing (SCM) architecture promises good performance in this scenario. The SCM links have the potential to multiplex multitude of radio signals carrying cellular Code Division Multiple Access (CDMA), Wireless Local Area Network (WLAN) and cable-TV (CATV) traffic in a single optical fiber. Table 1 summarizes the frequencies corresponding to cellular, IEEE802.11g WLAN and PCS networks. In such systems, a single central base station can be connected to many radio access points, which provide multiple services to the portable units, via SCM radio over fiber networks. Each radio access point can support cellular CDMA, WLAN or CATV services as required. Moreover, these services can be of high quality because of the short air interface.1

Typically, demultiplexing of subcarrier multiplexed signals is done by electrical domain bandpass filters. However, optical domain filtering of SCM signals gives multiple benefits. Because each subcarrier is independent, the desired subcarrier can be accessed at any point in the optical link/network if we have an all optical demultiplexer. Moreover with all optical demultiplexing, the receiver performance requirements are eased, the photodetector could be of low bandwidth and the receiver is needed to match only one subcarrier frequency. Furthermore, dispersion induced intermodulation products can be filtered out before their contribution as distortion mechanisms at the detector.2 In addition, cost-effective, passive and wavelength selective devices with high precision such as Fiber Bragg Gratings (FBGs) can be employed. The continuous development of such devices allows the subcarrier multiplexed fiber systems to benefit from optical signal processing.
Optical pre-filtering was first demonstrated by Greenhalgh et al., who suggested to utilize a Fabry-Perot etalon to filter a subcarrier prior to detection. The use of etalon, however, lead to distortion in the demodulated data and demultiplexing was possible only within a given time period. Chapmany et al. reported the use of a filter based on FBG in combination with Fabry-Perot. They achieved demultiplexing of microwave signals at 1.7 GHz and 2.44 GHz with the filter having a 3 dB bandwidth of 170 MHz. Previous research of optical demultiplexing has also been reported in systems incorporating both Wavelength Division Multiplexing (WDM) and SCM. However, typically the 3 dB bandwidth of the filter was in GHz range. Very little effort has been put into the investigation on demultiplexing of subcarrier frequencies at sub GHz range since, optical filters with very narrow bandwidth are required.

The focus of this paper is separation of subcarrier multiplexed cellular (900 MHz) and WLAN (2.4 GHz) microwave signals using our recently developed novel fiber Bragg grating (FBG) based sub-picometer bandpass filter. Owing to the appreciably narrow bandwidth of our filter, we were able to experimentally demultiplex signals at sub GHz range. In the following sections, we will first provide a brief theory on the generation of SCM signals. Then, the properties of the fabricated filter will be presented and the experimental results confirming the performance of the filter will be discussed.

<table>
<thead>
<tr>
<th>System Type</th>
<th>Frequency</th>
</tr>
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<tbody>
<tr>
<td>Cellular</td>
<td>900 MHz</td>
</tr>
<tr>
<td>IEEE802.11g</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>PCS</td>
<td>1.8 GHz</td>
</tr>
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</table>

Table 1 The operation frequency of few telecommunication systems

2. GENERATION OF SUBCARRIER MULTIPLEXED SIGNALS

In subcarrier multiplexing, each information bearing baseband signal is mixed with a local oscillator frequency, referred to as a subcarrier. The modulated carriers are subsequently summed via microwave power combiner. In links requiring high bandwidth, external modulation is a suitable method in imposing such radio frequency (RF) signals onto an optical carrier. In addition, it is possible to have fiber optic links with high gain. However, a drawback associated with the external modulation is that the sinusoidal behavior exhibited by Mach-Zehnder intensity modulator, limits the linear region to a small range. Therefore, it is necessary to operate the modulator in the linear region to minimize the unwanted non-linear distortion products.

Ackerman et al. described a model, where they derived the relation between the RF signal voltage and the Mach-Zehnder modulator output in the case of lumped element modulation. The instantaneous power at the output of the modulator is given by

$$P_{out,op}(t) = \frac{P_{in,op}}{2} \left[ 1 + \frac{sin \pi V_M}{V_\pi} \right]$$

where $P_{in,op}$ refers to the power available at the output of the laser and $V_\pi$ is the half-wave on-off switching voltage. $V_M$ denotes the voltage applied to the modulator and is described as

$$V_M = V_b + V_m1 sin(\omega_{sc1}t + \theta_1) + V_m2 sin(\omega_{sc2}t + \theta_2)$$

here $\omega_{sc1}$ and $\omega_{sc2}$ are the subcarrier frequencies for the independent channels and $V_m$ corresponds to the respective RF voltage. $V_b$ defines the applied bias voltage.

We can write the overall output power when subcarrier multiplexed RF signals are applied to the external modulator as follows. Note that it has unmodulated optical carrier ($P_{in,op}/2$) and two sidebands corresponding to each subcarrier.

$$P_{out,op}(t) = \frac{P_{in,op}}{2} \left[ 1 + \frac{sin \pi (V_b + V_m1 sin(\omega_{sc1}t + \theta_1) + V_m2 sin(\omega_{sc2}t + \theta_2))}{V_\pi} \right]$$
3. NARROW BAND FIBER OPTIC FILTER

Fiber Bragg grating has earned its place as an excellent optical filter in number of applications especially, in optical communications. Low insertion loss, passiveness, and high selectivity are few of the characteristics that makes it a good candidate as a selective device. Adopting fiber Bragg grating as an optical filter provides the most straightforward and low-cost approach. In this section, we will discuss the procedure involved in designing our filter.

If the length of the FBG is limited between 15 mm to 30 mm for the convenience of packaging, there are two ways to design FBG-based narrow band pass filters. One is to induce a $\pi$-phase in the middle of the FBG that will create a narrow pass band in the center of the FBG’s stop band. The drawback of this kind of filter is its higher insertion loss in the pass band. For example, a filter with a -3 dB bandwidth of 0.5 pm, fabricated in our laboratory, has an insertion loss of 8 dB. The other type is the FBG-based Fabry-Perot (FP) filter. When two highly reflective FBGs of identical wavelength form a resonator, the multiple reflections between them will create multiple resonant peaks in the stop band of the single FBG. The bandwidth of the resonant peak is determined by the spacing of the resonant peak and the reflectivity of the FBG. Since the high reflectivity FBGs between -20 to -40 dB can be easily fabricated, the bandwidth of the resonant peak of less than a picometer can be realized.

The filter used in this experiment, consisting of two FBGs of 12 mm in length separated by 4 mm, was written on an H2- loaded SMF-28 fiber and apodized with a sinc function. The center-to-center distance of two FBGs was 16 mm that gave the spacing of adjacent resonance wavelength of $\sim$73 pm. The stop bandwidth of the FBG was $\sim$0.3 nm at -3 dB so five resonant peaks can be observed as shown in Figure 1. However, the resonant peak was not fully resolved due to the limited resolution of 15 pm of the optical spectrum analyzer (OSA) used. Apparently, in order to measure an optic filter with a bandwidth at sub-pm level, a spectral resolution of several MHz is required (1pm$\approx$125 MHz in 1550 nm region). Since the microwave generator, used to modulate the optical carrier in this experiment, can step-scan the microwave frequency at 1 MHz resolution, one of the sideband of the carrier was used to scan through the middle resonant peak in Figure 1. The resonant peak with a very narrow bandwidth was confirmed. This is shown in Figure 2. The filter has a bandwidth of 120 MHz at -3dB, 360 MHz at -10 dB and 1.5 GHz at -20 dB, respectively. The filter is so narrow that the effect of birefringence, induced by the laser radiation during fabrication, was observed as the splitting of the resonance peak depending on the polarization of the light source. Figure 2 was obtained by aligning the laser polarization with the filter using a polarization controller. The low insertion loss of about 0.8 dB at resonant peak was also confirmed. The FBG-based FP filter is an all fiber device that can be relatively easily packaged with a thermally compensated design.

The spectral profile fits reasonably well with a planer FP resonator equation down to -15 dB, as shown in Figure 2, if the resonator reflectivity, R = 0.96 was used. The reason for mismatch of the spectral tails is a subject of the further study. One explanation is that the residual of amplified spontaneous emission (ASE) from the laser had leaked into the photodetector.

4. EXPERIMENT

In order to achieve demultiplexing of subcarrier multiplexed cellular and WLAN signals at 900 MHz and 2.4 GHz respectively and to characterize our demultiplexer, we performed number of experiments. We evaluated the performance and the feasibility of our designed sub-picometer filter together with an optical circulator in extracting 900 MHz from 2.4 GHz while the optical carrier was substantially reduced.

Figure 3 illustrates the block diagram of our experimental setup analogous to a downlink in a fiber based wireless architecture. A microwave signal carrying 5 Mbps data in Binary Phase Shift Keying (BPSK) format at 900 MHz was generated by Vector Signal Generator, SMIQ03B. This cellular signal was added with a WLAN signal (tone) centered at 2.4 GHz, generated by Synthesized Signal Generator, HP-8673B. The composite signal was superimposed onto the tunable laser output through a Mach-Zehnder modulator (MZM) that has a bandwidth of 13.9 GHz. We ensured an optimum polarization state to maximize the modulator output power by incorporating a polarization controller following the tunable laser. As a result of intensity modulation, an optical signal consisting of two lower- and two upper-sidebands with offsets of $\pm$7.2 pm (900 MHz) and $\pm$19.2 pm (2.4 GHz signal) from the carrier was produced. These are shown in Figure 4(a). Note that due to limited resolution
Figure 1. Transmission spectra of the narrow bandpass filter. The spectrum was measured with an OSA at 15 pm resolution.

Figure 2. The spectrum of resonant peak (solid line), obtained by scanning the sideband over a 2 GHz range at 4 MHz per step. The thin line was the calculated resonant spectrum from a planer FP resonator.
Figure 3. Experimental setup used for achieving demultiplexing of two subcarrier multiplexed microwave channels with the sub-picometer bandpass filter bandwidth (of 15 pm) of the optical spectrum analyzer (OSA), only the respective sidebands of the 2.4 GHz signal could be partially distinguished from the carrier. As the modulating subcarrier frequency is decreased the sidebands appear to be embedded within the carrier spectrum (and not visible). Figure 4(b) represents the MZM output under the same condition when the DC bias voltage of the modulator was tuned to linear region of operation. Still both sidebands are there, but not quite visible.

The optical carrier along with the four sidebands as given in Figure 4(b) were then fed into port 1 of the optical circulator. We integrated our designed bandpass filter in transmission state at port 2 of the circulator. The filter’s central resonant peak at 1536.5396 nm, as discussed in Section 3, was aligned with the corresponding lower sideband of the 900 MHz signal while the non-matching wavelengths were directed to the output port of the circulator. Figure 4(c) shows the extracted lower sideband of the 900 MHz. The filter was able to partly suppress the optical carrier, which bears no information, by 21 dB while considerably filtering out the WLAN signal. Note that the carrier power should not be completely removed to avoid distortion in the received RF signal. Hence, the carrier power was significantly reduced by the filter, but we still maintained the carrier-to-sideband ratio of 3 dB.

We employed a high speed optical-to-electrical (O/E) converter consisting of a PIN diode in detecting the filter output (cellular). Following, a Low Noise Amplifier (LNA) with a gain of ∼15 dB was deployed to have sufficient power in the microwave signal *. The amplified signal was fed into Wireless Communications Analyzer (WCA) to demodulate the signal into data streams. The bit-error-rate (BER) of the detected signal was attained

*as is typically done prior to transmission over the hostile wireless channel in practical systems
Figure 4. Optical spectrums obtained on the OSA (a) output of the MZM when the DC bias was tuned to non-linear region (b) output of the MZM when the DC bias was tuned to linear region (c) Lower sideband of the cellular signal selected by the filter through post-processing of eye diagrams recorded on WCA. Similarly, the rejected signal at port 3 was detected and demodulated. A minor difference may be observed between our arrangement and the practical wireless links. Commonly, in a complete fiber wireless link, the amplified radio signals via microwave amplifier are transmitted to an RF antenna, which provides services to both remotely located WLAN and cellular subscribers.

5. RESULTS AND DISCUSSIONS

To examine how well the output RF power at the filter output could follow the input RF power of 900 MHz, the input RF power was varied from -38 dBm to +6 dBm. Figure 5 shows the relatively linear relation between the input and the output. This demonstrated that our filter had almost linear characteristics within an RF power range of 44 dB. Hence the measured dynamic range of the filter is 44 dB. This could be even higher, but we could not verify due to limitations in our equipment.

The integrity of 900 MHz at the filter output was studied in terms of BER. The BER versus the input RF power is plotted in Figure 6, which depicts the high dependence of BER on the input RF power. An increase of 1 dB in the RF power increases the log(BER) from -6.62 to -8.73. The corresponding eye diagram of the received signal at an input RF power of +6 dBm is shown in Figure 7(a).

In order to evaluate the selectivity of our demultiplexer, we applied both the 900 MHz and the 2.4 GHz simultaneously to the modulator with equal RF powers. Then, we varied the input power of both signals and recorded the peak RF power levels at the output of the filter by using WCA. In this scenario, both signals were tones. Figure 8 shows that the filter had the ability to select the cellular signal by 25.5 dB more compared to the WLAN signal. The selectivity was constant with the increase in input RF power. Although the filter managed to suppress a substantial portion of the WLAN signal, we still observed some residual power, which we defined as leakage power. We observed that this leakage had negligible impact on the cellular signal. Figure 9 displays the dependence of the leakage power on the input RF power of 2.4 GHz.

In order to examine the integrity of the rejected WLAN signal, 2.4 GHz at port 3 of the circulator was amplified subsequent to O/E conversion and then sent to WCA to be demodulated. The eye diagram of the WLAN signal at the circulator output is seen in Figure 7(b), which shows a clear signal. It can be indicated that the bandpass filter played a negligible role in distorting the non-selected subcarrier.
Figure 5. Received RF power versus the input RF power for 900 MHz

Figure 6. Received BER versus the input RF power for 900 MHz
Figure 7. (a) represents the eye diagram of the 900 MHz (selected) signal obtained at the output of the bandpass filter (b) is the 2.4 GHz signal obtained at the output of the circulator (port 3)

Figure 8. Selectivity of the Demultiplexer
Our results show that BER is heavily dependent on the received RF power at the WCA. The BER showed here are estimated from the Q-factor. Therefore, a slight difference in the received power had a big impact on the calculated BER.

In addition, we observed that our system was subject to laser drift. Because the laser wavelength was tuned to coincide the corresponding lower sideband of 900 MHz to the central resonant peak of the filter, any drifting could change the power and vary the experimental results. This high sensitivity is mainly attributed to the fact that the filter has a 3 dB bandwidth in the sub-picometer range, and if the peak is not at the center of the LSB, the received power could be lower than anticipated.

6. CONCLUSIONS

In this paper, the characteristics of our newly designed sub-picometer fiber Bragg grating based optical bandpass filter was provided. We experimentally demonstrated demultiplexing cellular (900 MHz) and WLAN (2.4 GHz) signals in optical domain with this filter. Our results presented that with the narrow filter bandwidth in the picometer range and an insertion loss of 0.8 dB, it was possible to recover the filtered cellular and wireless LAN signals with about 25 dB isolation for over 44 dB dynamic range. Both the extracted and rejected signals showed clear eye diagrams which proved our filter does not introduce additional distortion. Our narrow bandpass filter can have potential use of optical demultiplexing of RF signal in networks employing subcarrier multiplexing.

REFERENCES

