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# AN OPTOELECTRONIC MULTIPLEXER FOR WIRELESS TRANSMISSIONS OF HIGH-SPEED DATA-MODULATED MICROWAVE SUB-CARRIERS

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**ABSTRACT:** *In this article, an optoelectronic multiplexing scheme is reported. This scheme results from the association of a multimode laser and the chromatic dispersion on standard single mode optical fiber. The frequency response of this system shows a series of microwave band-pass windows, which can be used for allocating modulated microwave subcarriers. Under this operating principle, the multiplexing of two data-modulated microwave subcarriers at 2.4 and 7.2 GHz is described in this work. 100 Mbps-NRZ and vector digital data (QPSK, mQAM) were transmitted and evaluated. The performance of the multiplexing scheme shows that it can be used for high-speed wired or wireless transmissions.* © 2016 Wiley Periodicals, Inc. Microwave Opt Technol Lett 58:486–490, 2016; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29593

**Key words:** *optoelectronic multiplexing; microwave subcarriers; radio links; wireless transmissions*

## 1. INTRODUCTION

Very often, high data rate transmission for telecommunications use multiplexed high-frequency subcarriers in order to accommodate wide-band information channels, prior to sending them through any transmission media such as cables, radiowaves, free-space optical links, and optical fibers channels. The multiplexing of different RF subcarriers normally imposes the use of highly selective electronic band-pass filters showing sharp transitions between the band-pass and cut-off responses. Design and realization of microwave band-pass filters is often based on planar or waveguide structures. However the design and realization of optimal filters is not a trivial task and a tradeoff between insertion losses, bandwidth, and filter order is required. Generally, several iterative design steps are often necessary in order to achieve wideband responses.

In an alternative approach, an optoelectronic multiplexing scheme is proposed in this article. This approach is based on the use of the microwave band-pass transmission windows of an optoelectronic scheme using a multimode laser diode (MMLD) and dispersive single mode standard optical fiber (SSMF) [1,2]. The band-pass windows perform as high-order band-pass filters. The location of the band-pass windows depend on the free spectral range (FSR) of the laser modes and on the length of the dispersive fiber. The band-pass response has been extensively studied and many papers reporting its potential use as microwave filters have been published [3–11]. In a perspective of practical applications, the band-pass frequency response can be used as an optoelectronic multiplexer for transmitting modulated microwave subcarriers. The band-pass response exhibits a sharp frequency transitions as to avoid the use of high-order electronic band-pass filters. The bandwidths of the transmission windows depend on the optical bandwidth of the laser modes and are typically of some hundreds of MHz. Such bandwidths are enough for grouping high-speed data-modulated microwave subcarriers for multi-channel wired or wireless transmissions.

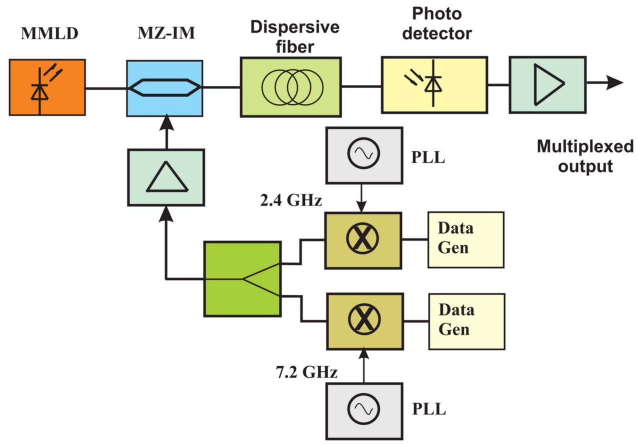


**Figure 1** Optoelectronic multiplexer, based on the association of a multimode laser and dispersive single mode fiber. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

To show a potential application, the optoelectronic multiplexing of two microwave subcarriers, centered at 2.4 and 7.2 GHz, is described in this article. These microwave bands are used for standardized telecommunications services; the first one is ISM (Instrumentation-Scientific-Medical)-band, around 2.4 GHz. The ISM band is strongly demanded as a variety of unlicenced services use it for transmitting high data rates. The best example is the extended use of the IEEE 802.11b/g/n standard for wireless local area networks (WLAN) [12,13]; the second one, in the 7–8 GHz band, is used for fixed and mobile satellite and space communications services (e.g., near earth and deep space telecommunications) [14–16]. The 7–8 GHz band is normally used for data transmission at relatively low rates and simple data formats (NRZ, BPSK, QPSK) [16].

These bands can be used for distributing multiplexed information over different media in indoor or outdoor environments.

## 2. OPTOELECTRONIC MULTIPLEXER

In this work, an optoelectronic multiplexer, based on a real multimode laser and dispersive SSMF, is described. The proposed scheme is illustrated in Figure 1.

As detailed elsewhere [1–3], the frequency response of the association of a multimode laser and dispersive fiber shows a series of band-pass transmission windows, centered at frequencies

$$f_n = \frac{n}{DL\delta\lambda} \tag{1}$$

$n$ is an integer; $D$ is the fiber dispersion parameter; $L$ is the optical fiber length and $\delta\lambda$ is the laser FSR. These windows, acting

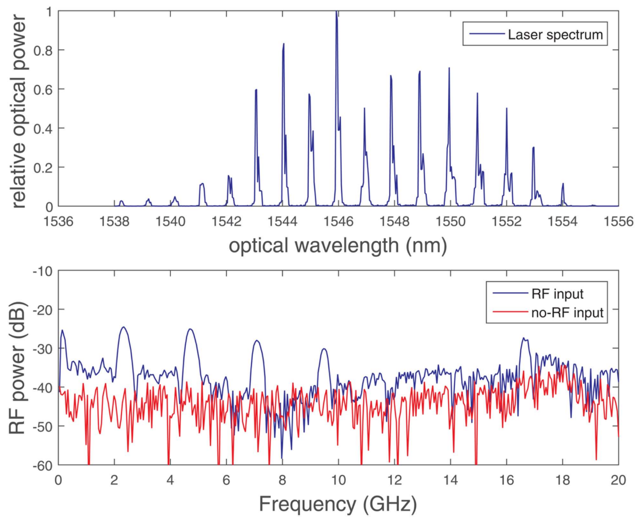


**Figure 2** (a) Multimode laser optical spectrum; (b) electrical response showing periodic band-pass windows. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

as sharp microwave filters, can be used for multiplexing modulated microwave sub-carriers, which are naturally isolated by the optoelectronic response. On depending of the laser parameters and the length of the optical fiber, the optoelectronic frequency response can be tuned-up. In this work, the generation of microwave band-pass windows centered at $f_n = 2.4n$ GHz ($n$, integer) was searched. This frequency response is achieved when using a multimode laser showing $\delta\lambda = 1$ nm and 25 km of SSMF [3].

To implement the optoelectronic multiplexer, the optical parameters of the laser are: $\lambda_0 = 1547$ nm; $\Delta\lambda = 10$ nm; FSR, $\delta\lambda = 1$ nm; mode FWHM, $d\lambda = 0.2$ nm. Figure 2(a) shows the measured spectrum of the multimode laser. In the scheme of Figure 1, the microwave frequency response is determined by modulating the laser light in a 0–20 GHz range using a Lithium Niobate ($LiNbO_3$) Mach-Zehnder modulator. Figure 2(b) depicts the measured RF response and also shows the measured noise floor, as a reference level when no RF is applied. According to the optical parameters, and in agreement with Eq. (1), the transmission windows are centered at $f_n = 2.4,\ 4.8,\ 7.2, \ldots$ GHz. The measured bandwidth of each transmission windows is about 300 MHz. The RF response can potentially be used for transmitting multiplexed analog or data-modulated microwave subcarriers.

The multiplexing of two data-modulated microwave subcarriers (two channel scheme), is described in the next section.

## 3. OPTOELECTRONIC MULTIPLEXING OF DATA MODULATED MICROWAVE SUBCARRIERS

The proposed optoelectronic multiplexer uses the 2.4 and7.2 GHz transmission windows for allocating two data-modulated microwave subcarriers. The 2.4 GHz band is used for the 802.11b/g/n WLAN standard. The 7.2 GHz is used for fixed satellite services and for scientific space communications. The multiplexing scheme has been tested in two complementary steps.

### *3.1. High Speed Digital Data Modulation*

In the first step, the microwave subcarriers were modulated by basic NRZ data streams, $2^{23} - 1$ PRBS, at a rate of 100 Mbps. The data comes from our available old BER test set (Anritsu ME522), which generates NRZ and RZ digital data up to 700 Mbps.

To evaluate the high-speed performance of the optoelectronic multiplexer when transmitting the 100 Mbps NRZ data stream, a 2-channel transmitter–receiver scheme has been implemented and tested. The scheme includes the optoelectronic multiplexer on the transmitter side and a receiver block, as depicted in Figure 3.

The 2.4 and 7.2 GHz modulated subcarriers were transmitted to the receiver block in a back-to-back configuration. The optoelectronic scheme ensures the band-pass filtering of the modulated subcarriers, centered at 2.4 and 7.2 GHz, as shown in Figure 4. Figure 4(a) shows the data modulated spectrum at the output of the electronic amplifier, before the electro-optical conversion. This spectrum shows overlapping harmonics coming from the two modulated subcarriers. Figure 4(b) shows the spectrum at the output of the optoelectronic multiplexer. It can be observed that the modulated subcarriers are naturally band-limited by the optoelectronic frequency response. The 100 Mbps data modulation is illustrated by Figures 5(a) and 5(b) on a zoomed view of the NRZ data spectra around 2.4 GHz and 7.2 GHz. The data-modulated spectra show the corresponding 100 MHz NRZ occupied bandwidth.

The proposed multiplexing scheme has been tested and the bit error ratio (BER) of the data transmission has been measured as the performance parameter. BER has been measured by demodulating the 2.4 GHz subcarrier. The optical power at the

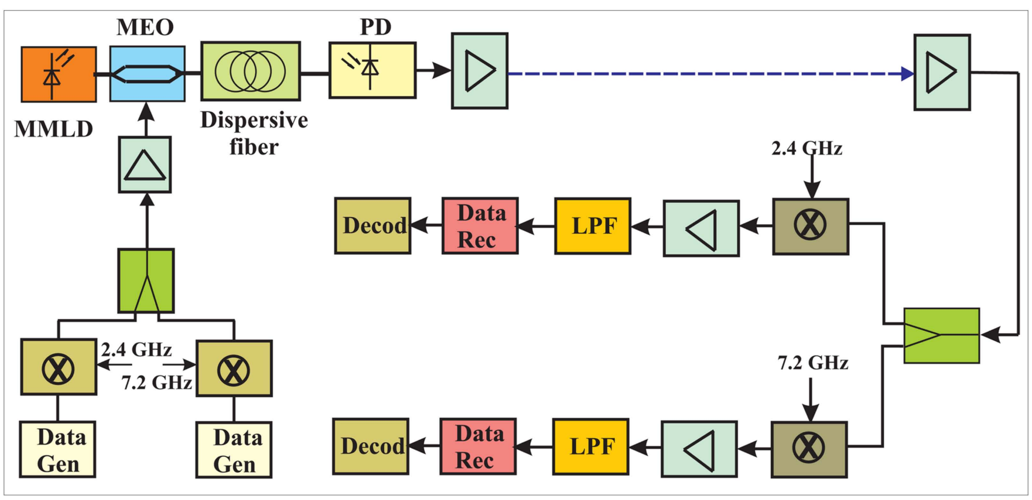


**Figure 3** Transmitter–receiver set-up for testing the optoelectronic multiplexed scheme. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

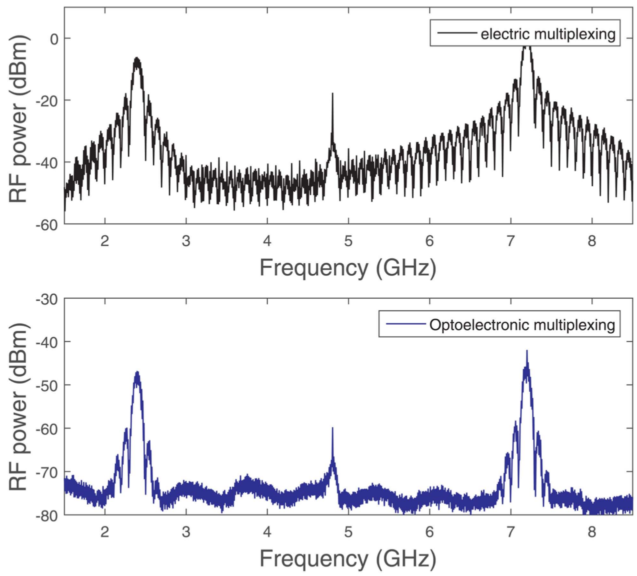


**Figure 4** Multiplexed data-modulated microwave sub-carriers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

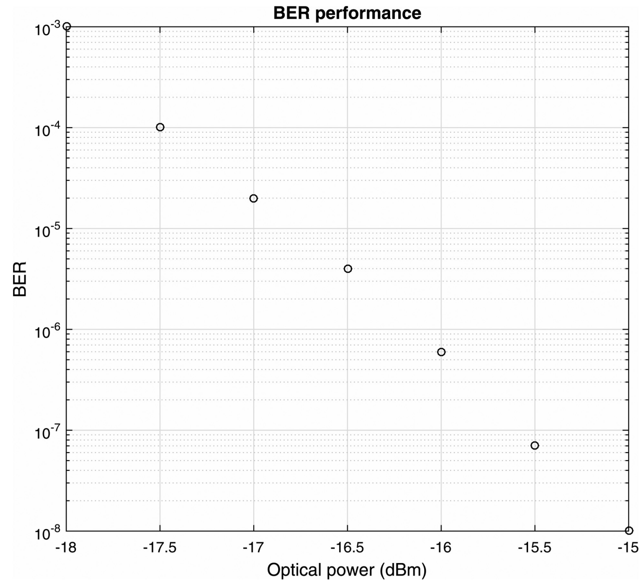


**Figure 6** Measured BER: demodulating the 2.4 GHz subcarrier

output of the electrooptic modulator has been taken as test parameter. The optical power was adjusted to −15 dBm, for ensuring a BER of $10^{-8}$ (this value is the measuring limit of our BER test set). The optical power was then attenuated in 1 dB steps and the BER was measured. The lowest BER of $10^{-3}$ was reached when the optical power is about −18 dBm. Figure 6 summarizes the measured BER.

### *3.2. Vector Signal Modulation*

In the second testing step, the microwave subcarriers have been modulated by multi-level vector signals, which are used in standard wireless protocols. As the 2.4 GHz band is extensively used for high-speed data rates and more complex modulation formats when compared to the 7–8 GHz band, the 2.4 GHz subcarrier has been modulated by vector signals, as proposed for transmissions using the 802.11n WLAN protocol [13,14]. The modulating signals include QPSK, 16 QAM, 64 QAM, and 256 QAM constellations. The optoelectronic multiplexer was evaluated by measuring the error vector magnitude (EVM), which is a main figure of merit when transmitting multi-level digital data. The combination of a vector signal generator and a vector signal analyzer allowed the evaluation of EVM. To show the measured vector data, Figure 7 illustrates the demodulated 2.4 GHz carrying QPSK modulation. Figure 7(a) shows the vector signal at the output of the vector generator (EVM=−38.8 dB); Figure 7(b) shows the same signal, at the output of the optoelectronic multiplexer (EVM=−35 dB). When using QPSK modulation, the 802.11n protocol can tolerate an EVM as low as −10 dB as transmission requirement for a coding rate of ½ [12]. The optoelectronic multiplexer EVM complies such a recommendation.

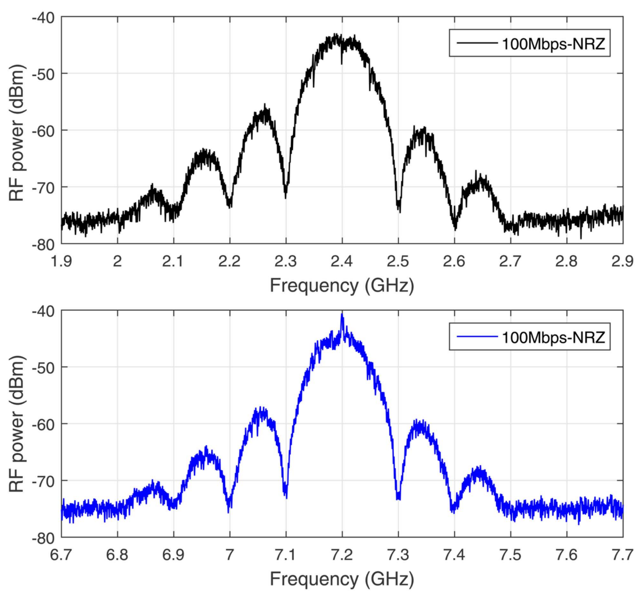


**Figure 5** 100 Mbps data-modulated microwave sub-carriers: (a) 2.4 GHz; (b) 7.2 GHz. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

As multilevel vector signals, such as mQAM, allow higher throughputs when compared to QPSK, the 2.4 GHz subcarrier was also modulated by 16, 64 QAM signals. Figures 7(c) and 7(d) illustrate the modulation–demodulation of 64 QAM signal. The generated 64 QAM (EVM=−40.0 dB) is compared to same signal at the output of the multiplexer (EVM=−36.6 dB).When using 16 QAM modulation, the 802.11n protocol can tolerate an EVM as low as −22 dB as transmission requirement for a coding rate of 2/3. The optoelectronic multiplexer EVM complies such a condition.

Table 1 summarizes the measured EVM for the different tested digital formats.

## 4. CONCLUSION

In this work, we have described the implementation of an optoelectronic multiplexer scheme on the 2.4 GHz and 7.2 GHz microwave bands. The multiplexer takes advantage of the band-pass transmission response, as generated by an optoelectronic scheme using multimode laser light and dispersive optical fiber. The band-pass response can be used for allocating high-speed data-modulated microwave subcarriers for telecommunications schemes, including wired and wireless links. Such capability has been demonstrated by multiplexing high-speed data-modulated

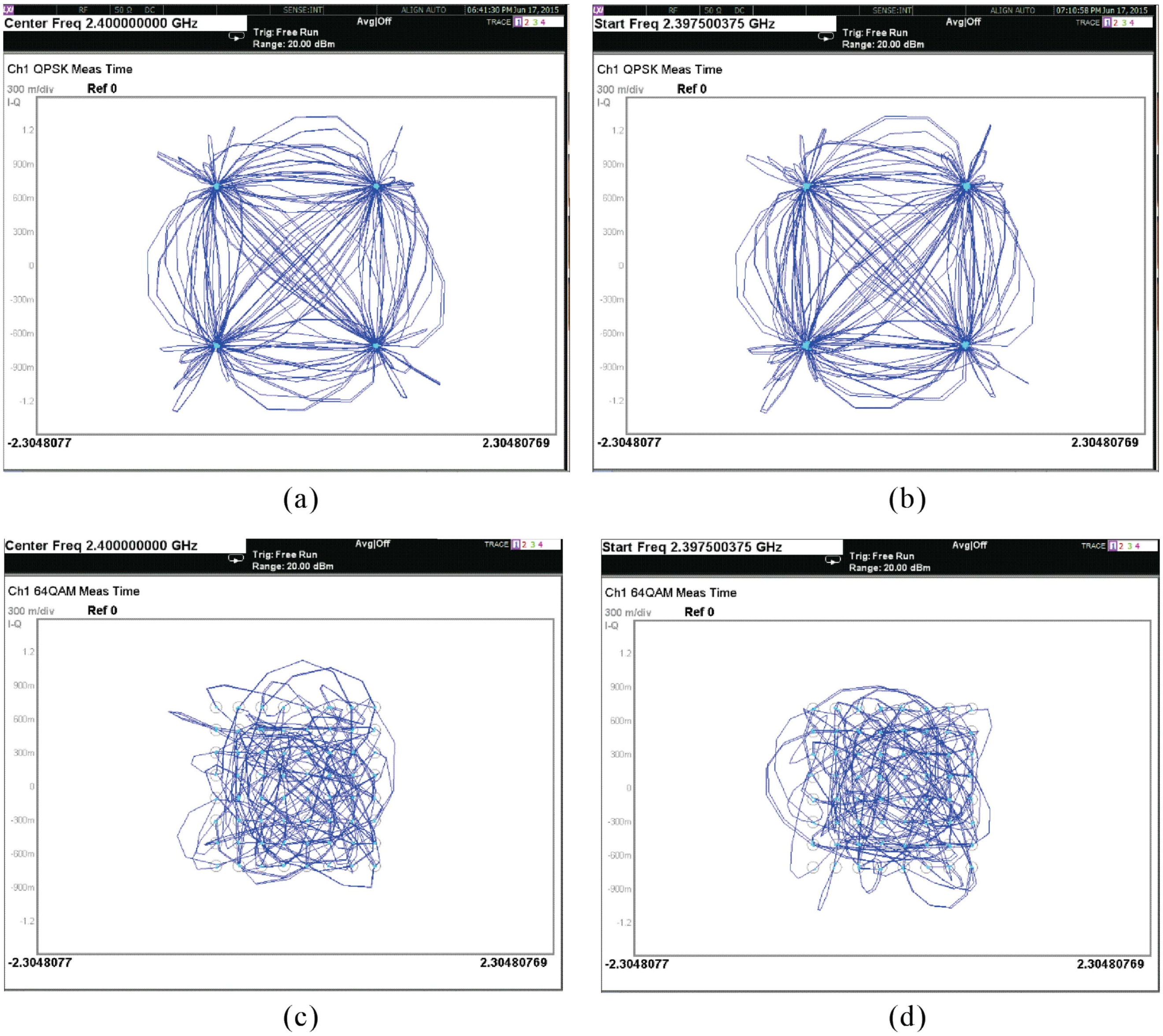


**Figure 7** Vector signals: (a–c) at output of the vector generator; (b–d) demodulation of the 2.4 GHz carrier at the output of the optoelectronic multiplexer. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

subcarriers. The performance when transmitting basic NRZ data streams gives BER of $10^{-8}$ and EVM less than 2% (−33 dB). The reported optoelectronic multiplexer can be used to multiplex more than two microwave subcarriers for transmitting high-speed information signals, either over wired or wireless transmission links that can be well adapted to the last-mile environment.

**TABLE 1 Measured VEM at the Output of the Optoelectronic Multiplexer**

| Data Format | EVM (dB) at Vector Generator Output | EVM (dB) at Optoelectronic Multiplexer Output | Recommended EVM at the Transmitter (dB) |
|---|---|---|---|
| QPSK | −39.0 | −35.0 | −10, codif. rate 1/2 |
| 16 QAM | −40 | −36.6 | −16, codif. rate 1/2 |
| 64 QAM | −40 | −36.6 | −22, codif. rate 2/3 |
| 25 6QAM | −40 | −38.0 | |

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# RECONFIGURABLE VIVALDI ANTENNA WITH IMPROVED GAIN FOR UWB APPLICATIONS

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**ABSTRACT:** *This article presents a new reconfigurable modified Vivaldi antenna with improved gain. A simple Vivaldi antenna is modified by adding slots in the extremities to demonstrate good radiation characteristics. The antenna reconfiguration is attended by inserting diodes PIN switches at specific localizations in the aperture antenna to change its resonance frequency. A wide bandwidth from 2 to 5 GHz and several narrow bands are obtained. This antenna is a good candidate for multi-applications necessitating frequency reconfigurable antenna.* © 2016 Wiley Periodicals, Inc. Microwave Opt Technol Lett 58:490–494, 2016; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29592

**Key words:** *Vivaldi antenna; ultra-waveband; reconfigurable antenna; modified antenna*

## 1. INTRODUCTION

Ultra-wideband (UWB) has attracted many researches. It has been utilized in many specific applications including biomedical detection, UWB radar applications, pulse communication, and ground penetration radar (GPR) [1,2].

Vivaldi antenna, which was firstly presented by Gibson in 1979 [3], is a better UWB antenna because of their excellent radiation performances including broad bandwidth, compact structure, higher gain, and radiation efficiency [4–6]. It is useful in UWB radar applications and UWB communication systems.

Due to its better performance Vivaldi antenna has attracted many research. Numerous methods were proposed to ameliorate the radiations characteristics of Vivaldi antenna such as adding slots, using metamaterials, adding dielectric resonator, etc. [7,8]. Modified Vivaldi antenna by adding slots in its extremities is a good method which offers a compact and reduced structure with improved radiation characteristics [9,10].

Recently, regrouping many services in one antenna by using reconfigurable antennas have received many attentions [11,12]. However, reconfiguring antenna is the best option which can reduce the interference level at the receiver, because that a fixed band will be selected at a given time [13,14]. Wideband to narrowband reconfiguration is necessary in modern telecommunication systems that enclose wideband and multimode applications [15,16]. Generally, frequency reconfiguration is achieved by using switches, such as micro-electronic mechanical system (MEMS) switches and PIN diodes, in specific position to drive the current distribution [13,14,17].

In this article, a reconfigurable modified Vivaldi antenna with improved radiations characteristics is proposed. UWB modified antenna with calculated slots is explained in section 2. Section 3 presents UWB to narrow bands reconfiguration design and discusses the simulation results for different states of switching. The conclusion of this article is presented in section 4.

## 2. ANTENNA DESIGN

Figure 1 shows the geometry of simple Vivaldi antenna designed on a 1.6 mm substrate with a dielectric constant of 4.7. The structure of the Vivaldi antenna is composed by dielectric substrate, metal ground plane, and feeding microstrip transmission line. The geometric parameters of the antenna are listed in Table 1. The exponential tapered slot which is on the ground plane can be expressed as:

$$Y = ae^{RX} + b \tag{1}$$

$$a = \frac{y_2 - y_1}{e^{rx_2} - e^{rx_1}} \tag{2}$$

$$b = \frac{y_1 e^{rx_2} - y_2 e^{rx_1}}{e^{rx_2} - e^{rx_1}} \tag{3}$$

where $(x_1, y_1)$, $(x_2, y_2)$ are the peak and bottom point respectively of the exponential tapered shape and $r$ is the exponential factor of the antenna.

To improve radiation characteristics of the antenna, series of symmetric slots is loaded in the extremities of the antenna. This modification is shown in Figure 2. Each slot operates as an RLC resonator where the resonant wavelength can be estimated by the following expression:

$$L = \frac{\lambda_0}{4}\sqrt{\frac{2}{1+\varepsilon_r}} \tag{4}$$

where $L_s$ is the length of slot and $\varepsilon_r$ is dielectric constant of the substrate. Five slots with varied lengths are added to achieve a wide bandwidth. The gradually decreased length of the five slots is listed in Table 2. The width of slot does not affect the return