Modulation accuracy of binary phase-shift keying signal broadcast after injection locking of a resonant tunnelling diode microwave oscillator
Cantú, H.I.; Patarata Romeira, B.M.; Kelly, A.E.; Ironside, C.N.; Figueiredo, J.M.L.

Published in:
Microwave and Optical Technology Letters

DOI:
10.1002/mop.27403

Published: 01/01/2013

Document Version
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

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\[
C_r = \frac{1}{L_1 \omega_0^2} \tag{3}
\]
\[
p = \frac{1}{\sqrt{2.2Z_0 \left(1 - \frac{c_0}{c_z} \right)}} \tag{4}
\]
where \(Z_0\) is the characteristic impedance of the system into which the unit cell's response is evaluated.

DGS section with the dimensions given in Table 1 has been used in the present design. Corresponding equivalent lumped element values of the unit cell are given in Table 2. Simulation results of the unit cell from EM simulation and circuit model are shown in Figure 4.

Geometrical parameters of the filter are given in Table 3. Electrical parameters of the filter are listed in Table 4. Analytical results (using MATLAB) were obtained by cascading individual ABCD matrices of three sections. Reflection and transmission parameters are extracted from the overall transmission matrix. Analytical results are compared against full-wave simulation results in Figure 5 and a close agreement between them can be observed. It can be noticed from Figure 5 that DGS improves the stop-band rejection characteristics of the filter better than 20 dB.

3. EXPERIMENTAL RESULTS

The filter is fabricated using standard printed circuit board fabrication technique. Figure 6 shows the photograph of assembled UWB filter. Experimental results of designed filter are compared against the full-wave simulation results in Figure 7. Comparison shows a good agreement between them confirming the expected UWB and wide stop-band rejection characteristics. Experimental results confirmed the extension of stop band up to 30 GHz with a rejection of better than 20 dB. The second harmonic (13.7 GHz) has been suppressed to a level of 25 dB. Measured group delay over the pass band is constant to within ±0.04 ns. Figure 8 shows the measured group delay. Filter is compact and measures dimensions of \(22 \times 22 \times 0.78\) mm\(^3\).

4. CONCLUSION

Using short-circuited meandered coupled lines along with the defected ground, a compact UWB filter with extended stop band was designed and analyzed in this article. An experimental filter while exhibiting 1.1 dB insertion loss and 13.5 dB return loss over the pass band of 3.1–10.6 GHz achieved a stop-band rejection of better than 20 dB up to 30 GHz. Overall dimensions of the compact filter are \(22 \times 22 \times 0.78\) mm\(^3\).

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communications link and also converted from optical to radio frequency domain using a RTD photodetector. Modulation accuracy is evaluated through error vector magnitude and bit error rate using computer software routines. © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 55:705–711, 2013; View this article online at wileyonlinelibrary.com. DOI: 10.1002/mop.27403

Key words: resonant tunneling diode; transceiver; phase-shift keying

1. INTRODUCTION

The availability of faster negative resistance devices such as the resonant tunneling diode (RTD) implemented as sources of microwave and millimeter wave radiation has made the mechanism of injection locking potentially useful for widespread applications in broadband communications systems [1]. Authors like Kurokawa [2] have previously described the phenomenon in detail with both quasi-static and dynamic analysis that can be used to develop circuit design techniques. The article in Ref. 3 demonstrated the possibility of injection locking of RTD-based microwave oscillators using the spectrally efficient communication scheme Gaussian minimum shift-keying (GMSK). The locked signal was broadcast and evaluated according to the modulation accuracy metrics of error vector magnitude (EVM), phase, and magnitude errors.

In this article, a binary phase shift-keyed (BPSK) signal is injected to a negative resistance microwave oscillator and then demodulated using a commercially available integrated circuit of the kind generally used for transmission of mobile digital communication standards (GSM, CDMA). The baseband data is generated by the computer software Matlab, which is also used to recover and evaluate the demodulated data from the receiver. This technique allows comparison between the original and the propagated bit stream for calculation of modulation accuracy parameters like the root mean square error vector magnitude (RMS EVM) and the bit error rate (BER). The effect of RF signal attenuation and baseband frequency on EVM and BER is investigated under the system conditions described in Section 2 for the case of a RTD-based transmitter configuration. Section 3 presents results of EVM and BER for an injection locked RTD receiver configuration. In Section 4, the light from a laser diode (LD) is modulated with the received locked BPSK signal. The photo-detected RF subcarrier is then demodulated and evaluated with EVM and BER metrics using Matlab.

In Section 5, a RTD-based oscillator is used as a photodetector and shown to be able to convert the BPSK signal from optical to RF domain even without an optimized coupling of light into the device. Conclusions of this article are included in Section 6.

2. RTD-BASED TRANSMITTER

A schematic representation of the wireless transmitter link is shown in Figure 1. The computer software Matlab is used to perform the following tasks: generate a pseudorandom bit sequence (PRBS) with 300 symbols, convert the sequence to a nonreturn-to-zero (NRZ) waveform, control the instruments required for baseband generation (Tx) and acquisition (Rx), and finally produce EVM and BER reports. For the present case, the BPSK symbol rate is equivalent to the bit rate which is established by the output frequency of the NRZ pseudorandom sequence produced by the arbitrary waveform generator (AWG) shown in Figure 1. The AWG output modulates a 1 GHz carrier through the In-phase baseband port of the commercial modulator AD8349. The modulator output RF is used to phase-lock the free running RTD-based oscillator which is also attached to a monopole antenna [4] by means of a circulator. There was no impedance matching optimization performed between the RTD oscillator and the other microwave components attached to the circulator.

The broadcast signal is received by a second antenna identical to the one used for transmission. The free-space path loss of the wireless propagation was adjusted to be 20 dB for all the cases studied in this article. Several attenuators were inserted between the circulator and the antenna in Figure 1 for the case when further signal attenuation was required.

The received RF signal is coupled to the AD8347 demodulator which recovers the In-phase baseband signal being monitored by a real time oscilloscope (RTO). The computer acquires the received waveform from the RTO after synchronization with the AWG triggering signal. The time delay between the Tx and Rx baseband waveforms was compensated manually and found to be between 45 and 70 ns for the measurements presented in this section.

A single AlAs/InGaAs/AlAs (13.2 μm2) double barrier quantum well RTD was used to implement the hybrid microwave oscillator shown in Figure 1. The circuit operates as a relaxation oscillator like those previously demonstrated in Ref.
3 based on the principles documented in Ref. 5. Figure 2 shows the tuning characteristics of the oscillator used in this article and the power generated by the device when the bias voltage is applied within the negative differential resistance (NDR) region of the RTD device. For the present article, the oscillator was tuned at a frequency of 1 GHz. The current–voltage characteristic of the RTD device is shown in the inset of Figure 2.

The carrier feedthrough of the modulator shown in Figure 1 was used to evaluate the phase noise improvement of the RTD-based microwave oscillator under phase-locking conditions. The feedthrough originates when the local oscillator (LO) signal used in the system has not been modulated and leaks through the RF output port of the AD8349. Figure 3 shows the phase noise improvement of the RTD-based microwave circulator operating at 1 GHz and injection locked to a −50 dBm carrier feedthrough. The locking range of the oscillator under these conditions indicated that the external quality factor Q of the circuit is below five.

Matlab software was used to generate an NRZ waveform and upload it to the AWG in Figure 1 by means of a GPIB interface. This waveform is used to modulate the 1 GHz LO signal (−20 dBm) through the AD8349 integrated circuit. The spectral characteristic of the produced BPSK signal is shown in Figure 4 for the case when the RTD device is NDR biased and unbiased. Injection locking of the oscillator is seen to provide 20 dB of signal gain to the BPSK signal broadcast.

Acquisition of 1000 waveforms and a total of 300 kbits were performed after transmission of a locked BPSK signal through

**Figure 2** Output power and frequency tuning of RTD-based oscillator

**Figure 3** Measured oscillator phase noise improvement after injection locking with modulator carrier feedthrough. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]
the system shown in Figure 1. The acquired data was stored in Matlab and used to calculate modulation accuracy parameters such as EVM and BER. The baseband sample rate was dependant on the repetition rate of the uploaded waveform and varied from 4.8 Msamples/s at 300 kbits/s to 320 Msamples/s at 20 Mbits/s.

2.1. Effect of Attenuation
The path loss between transmitter and receiver was increased for as much as 60 dB using connectorized attenuators. Table 1 shows EVM and BER reports for cases when several different levels of attenuation were added to the system. The total loss within the system is the 20 dB free-space path loss plus several values of connectorized attenuators attached between the circulator and the antenna of the transmitter. All cases reported had a BER below $3 \times 10^{-6}$, which means that no errors were found in the studied samples that contained 300 kbits. The results show that the $3 \times 10^{-6}$ BER can be obtained for a distance range above 20 m if the attenuators are replaced with increased free-space path loss between the antennas (assuming no multipath interference). For experiments performed with a total attenuation of 70 dB, the measured BER was $1.2 \times 10^{-4}$, which implies a system range above 70 m.

The experiments described in Table 1 took place at a fixed baseband rate of 300 kbits/s.

2.2. Effect of Increased Baseband Frequency
Injection locked oscillators have bandwidth limitations given by the relation between injected power and free running power [2]. It is well known that a locked signal can suffer distortion near the edges of the locking bandwidth due to the nonlinear response of the negative resistance oscillator. In this section, the effect of increased baseband bit rate was investigated over the modulation accuracy parameters measured in the system of Figure 1. A locking frequency range of 58 MHz was observed when a BPSK modulated signal with a power of $-22$ dBm and a bit rate of 300 kbits/s was injected to the RTD-based oscillator.

For these experiments, the LO ($-20$ dBm) used as the locking frequency of the system was tuned to the free-running frequency of the oscillator. The bit rate was varied by gradually increasing the frequency of the uploaded waveform repetition.

**TABLE 1 Transmitter link EVM and BER Measurements Vs. Attenuation**

<table>
<thead>
<tr>
<th>Total signal attenuation (dB)</th>
<th>36</th>
<th>43</th>
<th>47</th>
<th>50</th>
<th>53</th>
<th>60</th>
<th>20a</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM RMS (%)</td>
<td>5.2</td>
<td>6.8</td>
<td>7.7</td>
<td>10.0</td>
<td>13.0</td>
<td>17.3</td>
<td>8.8</td>
</tr>
<tr>
<td>Maximum EVM (%)</td>
<td>29.3</td>
<td>41.4</td>
<td>43.2</td>
<td>52.0</td>
<td>87.6</td>
<td>98.5</td>
<td>38.3</td>
</tr>
<tr>
<td>EVM percentile (95%)</td>
<td>10.4</td>
<td>13.4</td>
<td>15.1</td>
<td>19.6</td>
<td>25.3</td>
<td>32.7</td>
<td>17.6</td>
</tr>
<tr>
<td>BER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&lt;3 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

a RTD with no bias voltage.

**TABLE 2 Transmitter Link EVM and BER Measurements Vs. Bit-Rate**

<table>
<thead>
<tr>
<th>Bit rate (Mbits/s)</th>
<th>0.3</th>
<th>1</th>
<th>2.5</th>
<th>5</th>
<th>8</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM RMS (%)</td>
<td>4.7</td>
<td>4.6</td>
<td>5.6</td>
<td>6.2</td>
<td>11.9</td>
<td>11.6</td>
<td>28.8</td>
</tr>
<tr>
<td>Maximum EVM (%)</td>
<td>29.7</td>
<td>20.4</td>
<td>39.9</td>
<td>32.8</td>
<td>47</td>
<td>56.8</td>
<td>228.8</td>
</tr>
<tr>
<td>EVM percentile (95%)</td>
<td>9.5</td>
<td>8.4</td>
<td>10.4</td>
<td>11.9</td>
<td>27.4</td>
<td>24.5</td>
<td>64.0</td>
</tr>
<tr>
<td>BER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&lt;3 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Figure 4 Measured BPSK spectrum for several baseband frequencies
rate at the AWG. Figure 4 shows the measured spectrum at the output of the transmitter when the bit rate was varied from 1 to 20 Mbits/s. It is evident that above 10 Mbits/s a considerable distortion of the BPSK spectrum was taking place. Table 2 shows measured modulation accuracy parameters obtained from a gradual increase of the bit rate. Values of EVM and BER above 10 Mbits/s indicate a significant increase of detected errors as a consequence of the limited locking range of the RTD-based oscillator.

Figure 5 shows the received measured constellation diagrams for bit rates of 1 Mbits/s and 8 Mbits/s generated by Matlab. These diagrams show how the increased bit rate has produced significant dispersion of the symbol values around the nominal reference. Bit errors occur when the dispersion crosses from one side of the In-phase axis to the opposite side. At bit rates below 8 Mbits/s, BER values under $3 \times 10^{-6}$ were obtained.

3. RTD-BASED RECEIVER

A configuration was implemented with the locked RTD-based oscillator used to boost receiver power. The setup is shown in Figure 6. The signal generator in this case can be programmed to produce a BPSK modulated signal with an arbitrary waveform provided externally by Matlab. The baseband frequency can be set by changing both the sampling rate and repetition rate of the provided waveform (PRBS). The scope in Figure 6 is synchronized with the waveform repetition rate to capture the demodulated PRBS pattern. The pattern contains 256 bits and is repeated 2000 times for a total acquisition of 512 kbits. The wireless injected power to the receiver is 25 dB below the power of the free running RTD oscillator. With this level of gain, measurements of the modulation accuracy of the BPSK transmitted data were performed at baseband frequencies of 1.6 Mbits/s and 0.6 Mbits/s. The broadcast PRBS signal was obtained from demodulating the RF carrier using the integrated circuit AD8347. The bits are compared with the original sequence after correction of delay through the system. The correction is performed externally through numerical processing of the data acquired in Matlab. RMS EVM and BER results are reported in Table 3. Three bit errors out of 512 kbits were found at each baseband frequencies. There was no impedance matching optimization implemented for the setup shown in Figure 6.

4. LD MODULATION

The injection locked RTD oscillator at the receiver was used to directly modulate the output of a 1550 nm LD. The LD device is an InGaAsP Fabry–Pérot cavity laser that produces a 10 dBm beam output and can be modulated with frequencies as high as 10 GHz. The light is coupled to the tip of a lens fiber that has a working distance of 26 µm and a spot size of 5 µm. The fiber is attached to the input of an InGaAs PIN photodetector (PTV 2400-98) that converts the light back into the RF domain and provides the input signal to the AD8347 demodulator. Finally, the acquired waveform is sent back to a laptop computer to calculate modulation accuracy results and BER. A schematic representation of the scheme is shown in Figure 7.

**TABLE 3 Receiver Link EVM and BER Measurements**

<table>
<thead>
<tr>
<th>Bit rate (Mbits/s)</th>
<th>1.6</th>
<th>0.62</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM RMS (%)</td>
<td>8.2</td>
<td>8.9</td>
</tr>
<tr>
<td>EVM percentile (95%)</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>BER</td>
<td>$6 \times 10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 shows the baseband frequencies used in this scheme as well as the calculated EVM and BER. There was no optimization of impedance matching between the laser and the circulator nor the RTD oscillator and the circulator. The laser is DC decoupled from the rest of the circuit and biased independently to increase the amount of RF power output from the PIN photodetector. The power input to the demodulator is monitored through the second port of a splitter connected at the output of the PIN photodetector shown in Figure 7.

| TABLE 4 Laser Modulating Link EVM and BER Measurements |
|----------------------------------|------------------|------------------|
| Bit rate (Mbits/s)               | 1.6              | 0.62             | 0.31             |
| EVM RMS (%)                      | 10.2             | 8.9              | 15.5             |
| EVM percentile (95%)             | 24               | 20               | 38               |
| BER                              | \(1 \times 10^{-5}\) | \(1 \times 10^{-5}\) | \(<2 \times 10^{-6}\) |

5. RTD PHOTODETECTOR

The RTD device used in this article was designed with epitaxial layers that can absorb light at a wavelength of 1550 nm [6]. In this section, the light of a laser source was modulated with a BPSK signal using an electro-absorption modulator and then amplified with an erbium-doped fiber amplifier to a level of 10 dBm. The subcarrier of the light is photodetected by the RTD and used to injection lock the RF output of the 1 GHz oscillator. The experimental setup is shown in Figure 8.

Illumination of the RTD takes place from the top as illustrated in Figure 9 using a lens fiber. The lens fiber is identical to the one used in the previous section. Responsivity of the RTD has been estimated to be \(\sim 0.25 \text{ A/W}\) with coupling losses around 10 dB. The photodetected BPSK signal power was able to experimentally lock the RTD oscillator within a frequency range of 200 kHz.

The narrow locking range is limited by the layout of the device, which does not include a suitable window for illumination of the RTD epitaxial layers. The light is incident upon the device passivation layer, which reflects a considerable amount of power out of its active epistructure. An estimated photodetected power level of \(-50\ dBm\) managed to lock the RTD oscillator with the BPSK transmitted signal.
Previous experiments have shown, however, that with a suitable optical waveguide adapted to the RTD devices is possible to achieve locking bandwidths as broad as 24 MHz [7].

The locked RTD oscillator output in Figure 8 was directly connected to the AD8347 demodulator RF input. A baseband frequency of 80 kHz was used to measure the BER of a transmitted, photodetected BPSK waveform. The frequency was chosen after consideration of the narrow locking ranges observed earlier. The procedure to obtain BER was the same used in the previous section. A waveform was transmitted through the system, the delay was compensated externally in Matlab, and then the bits were extracted and compared with the original stream. Thirty bit errors were found within a sample of 512 kbits, which implies a BER of $6 \times 10^{-5}$. Here, it is important to mention that the AD8347 was designed to operate with baseband frequencies above 1 MHz, and as a consequence it adds considerable distortion to waveforms below that frequency. The RMS EVM was as high as 37%, however after symbol integration and recovery it was still possible to obtain a BER within the same order of magnitude of the results presented in the previous section ($<1 \times 10^{-4}$).

6. CONCLUSION

Several schemes of BPSK signal injection to a RTD-based microwave oscillator have been presented and evaluated in this article using RMS EVM and BER metrics. A wireless configuration of RTD-based transmitter and receiver have shown to operate at baseband frequencies above 1 MHz with RMS EVM and BER values below 8.5%, and $1 \times 10^{-5}$, respectively. The locked oscillator can also be used for optical networks applications alternatively as a direct modulator of a laser source or as a photodetector. Implementation of a receiver link with direct modulation of an output light source showed RMS EVM of 10.2% and BER of $1 \times 10^{-5}$ at a baseband frequency of 1.6 MHz. A demonstrator of the device deployed as a photodetector was shown to operate at a baseband frequency of 80 kHz with a BER of $6 \times 10^{-5}$. These results show that it is possible to design RTD-based components as the building blocks of communication system applications, where signal conversion between wireless and optical domains is required.

ACKNOWLEDGMENTS

The financial support of Fundação para a Ciência e a Tecnologia through the project PTDC/EEA-TEL/100755/2008—WOWi—Wireless-optical-wireless interfaces for picocellular access networks is gratefully acknowledged.

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ENHANCED WIDEBAND PERFORMANCE OF COUPLED FREQUENCY SELECTIVE SURFACES USING METAHEURISTICS

UFRN – Department of Communication Engineering, Federal University of Rio Grande do Norte, Caixa Postal 1655, CEP: 59078-970, Natal, RN, Brazil; Corresponding author: adaidlo@ct.ufrn.br

Received 19 July 2012

ABSTRACT: This article presents a bandwidth optimization study of two coupled frequency selective surfaces (FSS). The optimization is performed in two steps. In the first step, a genetic algorithm is developed to synthesize two single FSS crossed dipoles with resonant frequencies equal to 9.5 and 10.5 GHz, to be used in a broadside coupled geometry, separated by an air gap. In the second step, a particle swarm optimization algorithm is developed to determine the optimal value for the air gap length to optimize the geometry bandwidth. Prototypes are fabricated and measured to validate the optimization study results for the two coupled FSS structure. © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 55:711–715, 2013; View this article online at wileyonlinelibrary.com. DOI: 10.1002/mop.27451

Key words: FSS; evolutionary algorithms; particle swarm optimization; PSO

1. INTRODUCTION

Frequency selective surfaces (FSS) have been used in a wide range of applications such as radar antennas, printed antennas, satellite communication absorbers, and microwave ovens [1–3]. FSS are composed of periodic arrays printed on dielectric substrates that act primarily like filters. Usually each application has a number of requirements to be achieved by properly choosing the FSS element type, dielectric substrate material properties and thickness, geometry and configuration of the array cells. One of these important requirements is the enhancement of the FSS bandwidth that is accomplished using complex geometry elements in multi-layered structures [4, 0].

In this context, metaheuristics based on natural computing have been successfully applied in the development and optimization of FSS structures [6, 0]. A good example of these techniques is the particle swarm optimization (PSO), developed in the 1990s by Kennedy and Eberhart [8], inspired by the social behavior of a group of birds or a shoal of fishes. The fundamental concept of this technique is the ability of the particles to find optimal solutions to complex problems through their social interaction.

The optimization takes place in two steps. In the first one, a genetic algorithm (GA) is used to determine separately optimal structural parameters for two FSS structures, one with resonant frequency equal to 9.5 GHz, and the other one with resonant frequency equal to 10.5 GHz. These FSS optimized geometries are