FREQUENCY MODULATION APPROACH BASED ON SPLIT-RING RESONATOR LOADED BY VARACTOR DIODE

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Abstract. In the paper, an approach to frequency modulation is presented using a split-ring resonator (SRR) loaded by a varactor diode. The modulation occurs due to the continuous time variation of capacitance of the varactor diode via changing of its bias voltage by the signal which is necessary to modulate. The modulation signal is used for bias voltage. As a source of a carrier signal, one more extra magnetic loop antenna is utilized which is coupled with the SRR via near-field interaction. Investigation of two types of signals (harmonic and chaotic) was performed for modulation in the paper. It is shown that it is possible to provide the frequency modulation with deviation Δf = ±80 MHz which covers the frequency range 0.95...1.11 GHz for a 1 GHz carrier signal when a SMV1231 varactor diode is used. The major advantages of the suggested approach are the very simple design and ability to easily define the required values of frequency deviation through tuning of the bias voltage magnitude range of the varactor diode. Therefore, the presented investigation and results can be useful in the manufacturing of low-cost radio components.

Keywords: frequency modulation, varactor diode, split-ring resonator, frequency range, frequency deviation

ZASADA MODULACJI CZĘSTOTLIWOŚCIOWEJ NA BAZIE REZONATORA Z DZIELONYM PIERSCIENIEM OBCIĄŻONEGO DIODĄ POJEMNOŚCIOWĄ

Streszczenie. W pracy zaproponowano zasadę modulacji częstotliwości z wykorzystaniem rezonatora z dzielnym pierścieniem (SRR) obciążonego diodą pojemnościową. Procesy modulacji zachodzą poprzez ciągłą zmianę pojemności diody pojemnościowej, która z kolei następuje poprzez zmianę napięcia połówki rezonansowej. Sygnał modulujący służy jako napięcie polaryzacji. Zgodnie z sygnałem nośnym jest dodatkowa antena magnetyczna, która oddziewa poprzez bliskie pole polaryzacji z SRR. W pracy przeprowadzono badania w których jako sygnał modulujący zostały wykorzystane dwa rodzaje sygnałów: harmoniczny i deterministyczny chaotyczny. Wskazano, że przy zastosowaniu diody pojemnościowej SMV1231 i częstotliwości sygnału nośnego 1 GHz możliwe jest zapewnienie modulacji częstotliwości z odchyleniem Δf = ±80 MHz w pośmie częstotliwościowych 0.95...1.11 GHz. Zaletami proponowanej metody modulacji są bardzo prosta konstrukcja i możliwość łatwego ustawiania żądanej wartości odchylenia częstotliwości poprzez dostosowanie zakresu wartości napięcia przyłożonego do diody pojemnościowej. Przedstawione badania i uzyskane wyniki mogą być przydatne w produkcji tanich komponentów radiowych.

Słowa kluczowe: modulacja częstotliwości, dioda pojemnościowa, rezonator z dzielnym pierścieniem, zakres częstotliwości, odchylenie częstotliwości

Introduction

An SRR is a kind of left-handed metamaterial, characterized by a negative value of permeability \( \mu \) [5, 14]. Such a unique physical property was invented and described in [24] and is totally different from all natural materials where the permittivity and permeability are strongly positive. There are many approaches to manufacture both single SRRs and their arrays to utilize them at frequency ranges up to nanometer dimensions [7–8, 18, 28]. For instance, the microwave frequency applications of SRRs can be implemented by chemical etching on a dielectric substrate, as shown in Fig. 1a. Due to their high sensitivity, single SRRs [6–7] or surfaces based on SRR arrays [13, 19, 21] are successfully used for different applications such as a microwave sensor of small liquid inclusions [13, 21], the monitoring of organic tissue [19], permittivity sensors [4, 11], etc.

All applications of SRRs are possible due to the variety of their shape parameters including split width, gap distance, metal width and soldered capacitors or inductors as well as different resonator structures that are shown in detail in [1, 15]. Manipulating these constructive parameters allows the changing of SRRs' resonant characteristics which can be expressed via S-parameters. Each of the described approaches opens a lot of ways to tune the resonance frequency as required.

The physical dimensions of metamaterial components are predefined. For instance, in [26] a metamaterial was suggested that consists of asymmetric ring resonators which provide tuning by resonance frequencies via their shape deformation under the impact of thermal processes of the IR frequency range. Also, in [12], the dependence of the resonance values changing is shown through mechanical changing due to a ring stretching. Such approaches are quite inconvenient and characterized a low level of reliability. At the optical frequency range, the manufacturing of hybrid modulation systems using an SRR modified by an extra layer of graphene is very promising, though more expensive. An input signal of the described approach directly depends on the magneto-optical response of the structure [16, 27].

The most convenient method to control the resonances of SRRs is a time-varying tuning of the capacitance, for example by switching components with different values of capacitance by transistors or photoelements which work in key-mode and provide so-called on/off modulation [10–11]. However, topological and quite practical at the present time is the usage of varactor diodes, that is, components which can change their capacitance based on a bias voltage in a defined magnitude range [2]. Such an approach is utilized in the manufacturing of filters [22] and metasurfaces [9, 23], etc. Therefore, below, we suggest and investigate the possibility of adjusting the high frequency (HF) oscillations that appear in an SRR under the outer impact of low frequency (LF) ones, and of achieving the frequency modulation of harmonic and deterministic chaotic signals.

1. Theoretical description of SRR

A conventional SRR (Fig. 1a) consists of two cut rings with radii \( R_{out} = (R_{out} - R_{in})/2 \) and \( R_{out} = (R_{out} - R_{in})/2 \), where \( R_{out} \) and \( R_{in} \) are the outer and inner radii of the larger ring and \( R_{out} \) and \( R_{in} \) are the outer and inner radii of the smaller ring; and \( w_1 = R_{out} - R_{in} \) and \( w_2 = R_{out} - R_{in} \) are the widths of the outer and inner rings of the SRR, respectively. The distance between the outer and inner rings is \( s = R_{out} - R_{out} \). The gap \( g \) of each ring are rotated in a straight angle one from the other. The usual low-planar SRR is placed onto a dielectric substrate of height \( h \) and with permittivity \( \varepsilon \) as shown in Fig. 1a.

An SRR presents a conventional oscillator that equivalently corresponds to a usual LC-circuit as depicted in Fig. 1b. However, \( L \) and \( C \) are the total values of inductance and capacitance depending on several components. These values can be calculated through per-unit-length capacitance and inductance using complete \( K(\cdot) \) and complementary \( k'(\cdot) \) elliptical integrals [3, 6]:

\[
C_{pul} = 4\varepsilon_0 \left( \frac{k(\frac{g}{\sqrt{R_{in} \varepsilon}}) + \frac{1}{4}}{4} \right) \tag{1}
\]

\[
L_{pul} = \frac{1}{c^2 C_{pul}} \tag{2}
\]

where \( c \) is the speed of light.
The total capacitance and inductance values are expressed as:
\[
C = \frac{r \theta}{4} + 2C_g \quad (3) \\
L = g \theta + 2L_g \quad (4)
\]
where \(2C_g = C_f + C_s\) for \(C_f = C_s\) which can be calculated from [20]; \(r\) is the effective radius, and \(\theta\) is the effective angle appearing due to the strips’ curvature. \(L_g\) is described by Rosa’s formula [17, 29]. Finally, the resonance frequency of an SRR can be found using the well-known Thomson’s formula \(f = 1/(2\pi\sqrt{LC})\).

2. Experimental measurements of the suggested modulation principle

The suggested modulation device is presented in Fig. 2a. It includes an SRR that is manufactured by chemical etching on a FR4 dielectric substrate where one of the gaps is substituted by a soldered varactor diode \(VD\). This gap is connected to a modulation signal generator (MS) via an SMA connector. The \(m(t)\) signal provides the varying of total capacitance changing \(VD\) bias voltage. In the experiment, an SMV1231 varactor diode was utilized where its capacitance can change \(\Delta C = C_{\text{min}}-C_{\text{max}} = 2.35 \ldots 0.534 \ \text{pF}\) for reverse voltage changing \(\Delta U = U_{\text{min}}-U_{\text{max}} = 0 \ldots 7\ \text{V}\) [29], where the \(\text{min}\) and \(\text{max}\) indexes indicate the values of capacitances for the minimum and maximum values of the voltages, respectively. By changing one of the capacitances from the equivalent circuit of Fig. 1b and keeping in mind their serial connection, one can obtain the ratio (5) from calculations of the resonant frequency following Thomson’s formula using (1)–(4):

\[
\frac{f_{\text{CMS}}}{f_{\text{CS}}} = 0.86 \quad (5)
\]

The equivalent circuit of the modulator is shown in Fig. 2b. The SRR loaded by a varactor diode is presented by the resonant circuit \(L1C1VD\). A source of the modulation signal \(MS\) generates the LF signal (harmonic or chaotic) \(m(t)\). The carrier signal \(M(t) = \cos(2\pi f_c t)\), where \(f_c\) is a frequency of the carrier signal, is supported by HF signal generator \(CS\). This signal, via a circulator and then through the magnetic interaction between \(L1\) and \(L2\), is transferred to the oscillator where the frequency modulation occurs. Then, via the \(L1L2\)-subcircuit and circulator, the modulated signal \(S(t)\) is transmitted to the communication channel. In the experimental setup, a usual magnetic loop antenna was used as the \(L1L2\)-subcircuit.

In order to begin the experimental investigation of the frequency modulation by the proposed approach, it is necessary to check the operational voltage range of the used varactor diode which will be further supplied to the signal \(m(t)\). It was measured through the \(S_{11}\) parameters of the used magnetic loop antenna. It was determined that the operating frequencies are restricted to the range of \(\Delta f = 0.95 \ldots 1.11\ \text{GHz}\) for \(f_c = 1\ \text{GHz}\) (the deviation value of frequency \(\Delta f = \pm 80\ \text{MHz}\)) for the voltage range \(\Delta U = -4.0 \ldots 3.0\ \text{V}\) (Fig. 3). In this case, the modulation index was \(\beta = 0.078\). The obtained frequency range satisfies expression (5). It is the maximum possible frequency range for the selected varactor diode and it can be tuned as required by establishing the minimum and maximum values of bias voltage. This allows the required frequency range to be controlled.

![Fig. 1. The usual low-profile SRR on a dielectric substrate (a), and its equivalent LC1C2-circuit (b) ![Fig. 2. Experimental setup of the suggested frequency modulation principle that consists of an SRR loaded by a varactor diode and magnetic loop antenna to supply the HF carrier signal (a), and its electrical circuit which includes modulation (MS) and carrier (CS) signal generators interacting with the SRR via a strong near magnetic field (L1-L2) and circulator (b) ![Fig. 3. Experimentally measured S11-parameters’ frequency dispersion, which defines the operation frequency band of the investigated modulator setup.](image-url)
For the first experimental studying of the frequency modulation following the approach from Fig. 2, the harmonic signal \( m(t) = \cos(2\pi f_m t) \), where \( f_m \) is the frequency of the modulation signal, was provided by generator MS. The amplitude values corresponded to the determined range above \( AU \) (Fig. 3). We investigated a number of harmonic signals with values of \( f_m \) up to 10–20 MHz. Further increasing of \( f_m \) is restricted by the characteristics of the varactor diode. The normalized power spectrum of modulated signal \( S(t) \) with frequency \( f_m = 1 \) kHz is shown in Fig. 5. It corresponds to the above-calculated deviation value and ratio (5).

Investigation of the modulation of the broadband signal was carried out. Two different chaotic oscillations were utilized which are deterministic chaotic oscillations of Chua’s scheme. These two signals are broadband and characterize continuous power spectra with 5 kHz of bandwidth. The signals’ amplitudes were controlled to not exceed the defined range of \( AU \). As a result, the normalized spectra of both modulated signals are shown in Fig. 5 which also satisfies the deviation value and ratio (5).

3. Experimental investigation of demodulation

Experimental investigation of the demodulation process was implemented through an IQ-demodulator scheme. Its equivalent circuit is shown in Fig. 6. The operational principle of the used IQ-demodulator is that a HF signal \( S(t) \) from a radio channel splits between two branches of the circuit. The split signal \( S_f(t) \) interacts with the HF signal \( M_f(t) = \cos(2\pi f_1 t) \) via Mixer1 and as a result, signal \( Q(t) \) is received at the second output of the demodulator. \( I(t) \) and \( Q(t) \) are the components of complex value of the detected signal MS and can be written as \( m(t) = I(t) + iQ(t) \), where \( i = \sqrt{-1} \). In order to recover the initial modulation signal \( m(t) \), it is necessary to determine the module of the detected signal as \( m(t) = \sqrt{I^2(t) + Q^2(t)} \).

In the experimental process, we explored the modulation of a number of harmonic signals with different values of frequency up to the maximum possible. For presentation in this paper, we picked up the harmonic signal \( m(t) \) at a 5 MHz frequency. The experimentally obtained \( I(t) \) and \( Q(t) \) signal and their spectral characteristics are shown in Fig. 7 as a screen of the used oscilloscope. The obtained spectral characteristics contain the main harmonic component at the correct frequency.

4. Conclusions

In this paper, a frequency modulation principle was suggested using an SRR loaded by a varactor diode. Changing of a bias voltage (LF modulation signal) of the utilized varactor diode allows the resonant parameters of the SRR oscillator to be tuned. The carrier signal was fed from a HF generator via an additional magnetic loop antenna through the strong near-field interaction with the SRR.

The experimental investigation was carried out for harmonic and chaotic (broadband) signal modulations. For the case where a SMV1231 varactor diode is used, the maximum range of frequency deviation \( \Delta f_m = \pm80 \) MHz (the modulation index \( \beta = 0.078 \)) can be achieved, and for a 1 GHz carrier signal, it occupies the frequency range \( \Delta f = 0.95 \ldots 1.11 \) GHz. However, the obtained spectrum band can be controlled and established by tuning the amplitude of the bias voltage.

We strongly believe that the presented investigation and obtained results are useful in the manufacturing of low-cost radio components.
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