Paper

High Q-factor Fabry-Perot Microresonator as an Alternative to Microdisk in Electro-Optical Modulator for Microwave-Photonic Receivers

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Abstract—In the last decade a new idea has been suggested for receivers of communication systems, namely, in microwave receivers' architecture. Though superheterodyne radio-frequency receivers are best suited to the needs of contemporary wireless communication, however stray radiation of their local oscillator (heterodyne) interferes with neighboring radio-devices and permits to locate the covert receiver. To overcome this drawback the signal transfer to optical range has been suggested. By this conversion, not only an elimination of receiver's stray radiation is attained but also vast advantages of photonic signal processing become available. The key element of existing microwave-photonic receivers is electro-optical microdisk modulator. However, its realization is complicated and as an alternative an electro-optical modulator based on high Q-factor Fabry-Perot microresonator is suggested. Comparative analysis of both types of modulators is performed, and advantages of high Q-factor Fabry-Perot microresonator based modulator are highlighted.

Keywords—electro-optical modulator, microwave-photonic receivers, wireless communication.

1. Introduction

In the last decade microwave (MW) communication systems expand rapidly the frequencies of their operation. While increase of operating frequencies is advantageous on the subject of communication speed, it revealed the serious problem related to the receivers' structure. The contemporary communication systems are exploiting superheterodyne radio-frequency (RF) receivers as they best satisfy the requirements of modern communication systems. These receivers have higher selectivity and sensitivity compared to the other types of receivers [1]. However, with the increase of operating frequency the stray radiation of heterodyne (local RF oscillator) is increased. This parasitic radiation becomes a source of interference for neighbouring radio devices. Moreover, what is undesirable, it is possible to locate the covert radio receiver and its operating frequency by means of this parasitic radiation. All this demands serious revision of MW receivers' construction.

There are several ways to reduce a stray radiation. One of them is the use of a stop-band filter on the way to antenna. The presence of this filter brings to the lessening of parasitic radiation, but does not eliminate it. Parasitic radiation may be reduced also at the expense of the schematic complication of the superheterodyne receiver [2]. While this method increases the size of the receiver and its power consumption, it cannot completely get rid of parasitic radiation. As the proper way out, the transition to the intermediate optical range has been suggested [3]–[7]. The essence of this approach is application of optical local oscillator (laser) instead of RF one. In this type of receivers, an incoming MW carrier loaded by low frequency signal, after passage through the RF input circuit is converted to the optical domain where advantages of optical signal processing can be exploited [8]–[10]. In the end, a photodetector retrieves the low-frequency signal. In this kind of a combined receiver, so called MW photonic receiver, besides getting rid of parasitic radiation in RF range, it is possible to attain the requiring sensitivity, selectivity and bandwidth, while having immunity to the external electromagnetic stray radiation, small size, weight and power consumption [3]–[7], [11]–[14]. The block-diagram of a MW photonic receiver is presented in Fig. 1.

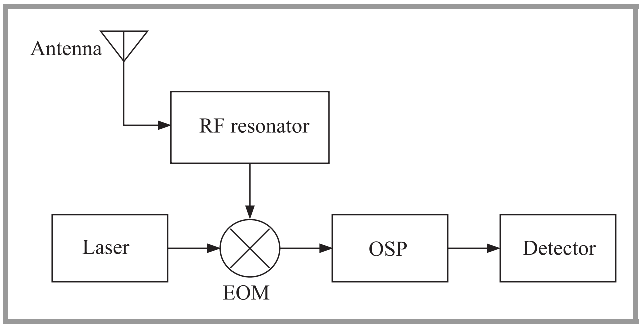

Fig. 1. Block diagram of microwave-photonic superheterodyne receiver: EOM – Electro-Optical Modulator, OSP – Optical Signal Processing.

To ensure high sensitivity and selectivity of this type of combined receivers it is necessary to have high Q-factor in the RF input part and high efficiency electro-optical transformation. While high Q-factor MW input circuitry is well established, the problem is finding a proper electro-optical modulator (EOM), which would ensure strong interaction between electrical and optical waves. This is possible only in optical resonant structure. The last permits to prolong electrical field interaction with optical wave confined within the resonator. From the known optical resonators for microwave-photonic receivers Fabry-Perot (F-P) and disk or ring one are the most suitable. The confinement of optical wave in F-P resonator depends on the reflectance of mirrors serving also for light input and output from the resonator. Higher is the mirrors' reflectance, stronger is the confinement of light within the resonator. The confinement is proportional to the light survive time within the resonator. In disk or ring resonators, an input/output of light from the resonator is performed through coupling via evanescent waves between disk and prism. These two types of resonators are described by the same mathematics and can be characterized with the same parameters, and their application depends on the feasibility [15]. An initial realization of MW photonic receiver is relied on EOM based on high Q-factor microdisk resonator [3]–[7], [11]–[14]. Recently the structure of EOM based on high Q-factor F-P microresonator has been suggested [16]. Below the brief description of both types of modulators is presented and advantages of F-P microresonator are discussed.

2. Electro-Optical Modulators of Microwave Photonic Receivers

2.1. Microdisk Electro-Optical Modulator

The first circular optical modulator for a microwave-photonic receiver was demonstrated in 2001 where a $LiNbO_3$ microdisk cavity has been used [3]–[5]. EOM uses a z-cut $LiNbO_3$ disk resonator with optically polished curved sidewalls (Fig. 2a). Evanescent prism-coupling is used to couple laser light into and out of a resonant TE-polarized high Q-factor optical whispering-gallery mode (WGM) which exists at the periphery of the disk. A metal electrode structure fed by an RF signal is designed to overlap with the optical field. The resonator's high optical Q-factor is used to increase the effective interaction length of photons with an applied RF microwave field. Combined with a simultaneously resonant microwave structure a highly sensitive receiver at microwave frequencies is achieved [3]–[7], [11]–[14]. Schematics of the receiver proposed for millimeter wave RF detection is presented in Fig. 2b [5].

An electromagnetic wave received by a RF antenna feeds electrodes of the microphotonic modulator. The modulator directly converts the RF signal to an optical carrier via the electro-optic effect. The phase- modulated optical signal is internally converted to amplitude modulation through interference with previous optical round trip.

The typical radius of $LiNbO_3$ microdisk is $R = 3.18$ mm and the thickness is $h \leq 1$ mm for operation at 7.67 GHz.

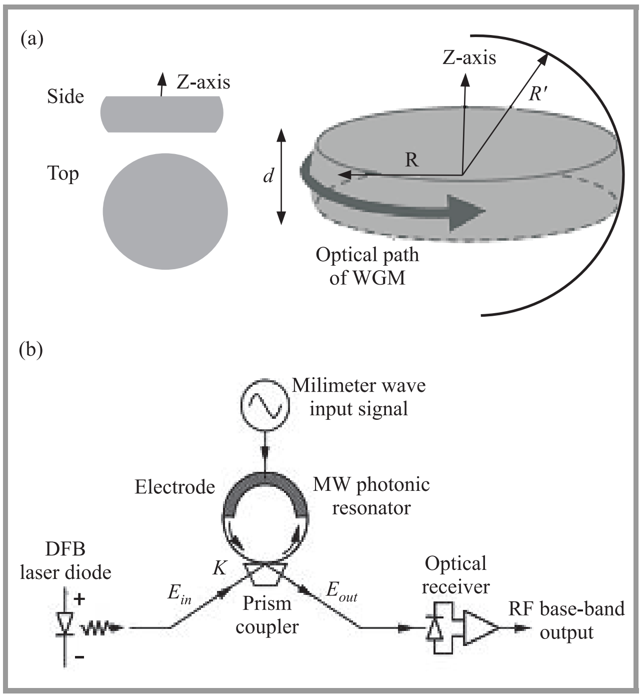

Fig. 2. Geometry of a microdisk: R – disk radius, d – disk thickness and curved side walls with radius of curvature R' (a); the receiver proposed for millimeter wave RF detection (b).

The sidewall of the disk is optically polished with a radius of curvature R', which typically is equal to the radius of the disk. For operation as MW resonator, the gold electrodes are located on the top and bottom of the microdisk. RF signal from the microstrip line is applied to the metallic electrodes. For optical part operation, a single-mode laser injects optical WGMs inside the microdisk (at $\lambda_0 \approx 1550$ nm). The trapezoidal prism is used to input and output an optical radiation from the microdisk by means of evanescent waves. For this, the air gap between the microresonator and the prism should be about the optical wavelength to fit the optimal connection between the prism and the microdisk. The typical quality factor Q for the considered microdisk is $4.1 \cdot 10^6$, and the free space range (FSR) of optical spectrum is 7.67 GHz [3]–[5]. The resonant interaction of MW radiation with optical wave in the microresonator takes place when the microwave frequency is a multiple of the FSR of the microresonator. The frequency of the microwave carrier f_{MW} should be an integral multiple m of the optical FSR of resonator such that $\Delta f_{FSR} = \frac{1}{\tau_{disk}} = (2\pi Rn/c)^{-1}$ where τ_{disk} is the optical round-trip time of the disk, R is the radius of disk and n is the refraction index of $LiNbO_3$ in the corresponding optical range [3].

The semi-ring electrode is a standing-wave resonator with open ends so its resonant frequency can be easily tuned by changing its length. This property has made the semi-ring the preferred resonator in most microdisk modulator designs. The optical WGM is confined around the microdisk equator (due to the side-wall curvature) and the modulating electric field is confined between the electrode and the ground around the microdisk so the electro-optical overlap is relatively large. Due to the RF resonance in input electric circuitry the voltage across the microdisk larger than that of the input. The small thickness of the microdisk transforms the applied voltage to a large modulating electric field. Such modulators allow efficiently implementing microwave optical conversion and assuring required sensitivity and selectivity of contemporary microwave photonic receivers. However, challenges in fabrication of $LiNbO_3$ microdisks and demands in precision tuning of a microprism (serving for input and output of optical radiation into microdisk) hinder from their wide application. The last is confirmed also by the modest list of references in this area.

To get rid of above-mentioned complications it has been suggested to replace $LiNbO_3$ microdisk with a high Q-factor planar F-P microresonator based on $LiNbO_3$ operating element [16]. Planar configuration of a microresonator has advantages in realisation and the usage of a microprism stands no longer.

2.2. High Q-factor Fabry-Perot Resonator Based EO Modulator

It is known that F-P and microdisk resonators are identical with their optical characteristics and mathematical description, and therefore the choice of resonator's type depends on its feasibility [15]. These two types of microresonators (F-P and microdisk) differ by the round-trip. In the microdisk one the round-trip L_{RT} is equal to its circumference $L_{RT} = 2\pi R$, where R is the microdisk's radius. In the F-P microresonator $L_{RT} = 2L_{FP}$, where L_{FP} is the distance between the mirrors of the microresonator. The prototype of an EOM based on F-P microresonator is shown in Fig. 3 [16].

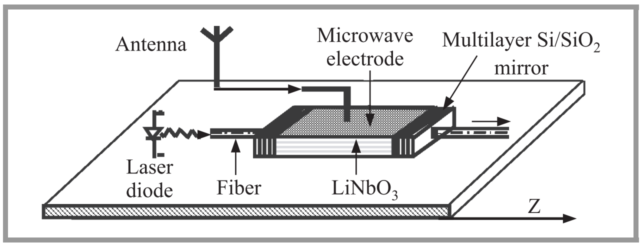

Fig. 3. Electro-optical modulator based on F-P microresonator with the multilayer mirrors.

The operating part of the microresonator based on the z-cut $LiNbO_3$ wafer. Multilayer mirrors at the transversal facets are alternating quarter-wavelength Si/SiO_2 layers implementing high Q-factor of optical microresonator. For input and output of light polished ends of fibers are tightly adjoined to multilayer mirrors. The top and bottom lateral facets are covered with layers of metal for microwave field supply.

Numerical simulation of optical characteristics of EOM based on F-P microresonator for application in MW photonic receivers is performed by the method of single expression [17]–[19]. The microresonant structure consisting of $LiNbO_3$ plate sandwiched between mirrors consisting of three pairs of quarter-wavelength layers of Si/SiO_2 allows attaining optical spectral characteristics identical with that of the microdisk optical microresonator [16]. The results of numerical simulations permit to assert that the proposed EOM based on F-P microresonator can be offered as an optically identical with microdisk resonator and can be considered as an alternative to the microdisk one.

Electro-optical characteristics of a modulator based on F-P microresonator are analysed by means of numerical simulation [20]. In the analysis an instantaneous change of the value of permittivity of $LiNbO_3$ plate under applied MW field is assumed. MW field is applied normally to the plate's plane.

At the optical resonance photons within the microresonator make a number of round-trips. When MW field is applied, any uncompensated change of the microresonator's local permittivity along the round-trip path of photons destroys the resonant state that is observed as an amplitude modulation in the output light.

Interaction of the MW field with the optical wave at the full coverage of the microwave top electrode along the F-P microresonator is considered. Interaction takes place due to second-order nonlinearity of $LiNbO_3$. It is known that the variation of the refractive index of $LiNbO_3$ crystal by the amplitude of applied electric field is expressed as: $\Delta n = n^3 \cdot r(33)E/2$, where $n = \sqrt{\varepsilon}$ is the refractive index at the absence of external electric field, $r(33)$ is an electro-optic coefficient of the material [4], [5]. According to the change of the sign of electric field (namely, to the change of its direction in space) the variation of the refractive index Δn changes the sign. As a result, an optical wave propagating in the microresonator meets the medium of changed permittivity, and as a consequence moves with varying phase velocity. By taking into account instantaneous change of the value of permittivity of $LiNbO_3$ plate under the applied sinusoidal MW field, the phase velocity of the optical wave V will depend on the value and frequency of MW field as follows:

$$V(t) = \frac{c}{\sqrt{\varepsilon + \alpha \cdot \sin(\omega t + \varphi)}}, \tag{1}$$

where c is the speed of light in free-space, ε is the permittivity of $LiNbO_3$ plate at the absence of external MW field ($\varepsilon = 4.5$ at $\lambda_0 = 1550$ nm [4]), α is a coefficient of influence of MW field on the permittivity of $LiNbO_3$ plate (this value is determined by the product of electro-optic coefficient $r(33)$ and electric field amplitude of MW field), ω is the frequency of the MW field, φ is the phase of the MW field.

To obtain the frequency dependence of influence degree of sinusoidally changed MW field on the phase velocity of optical wave in F-P microresonator, it is sufficient to consider this process in the course of a round-trip in the microresonator. Efficient interaction of MW field with optical wave

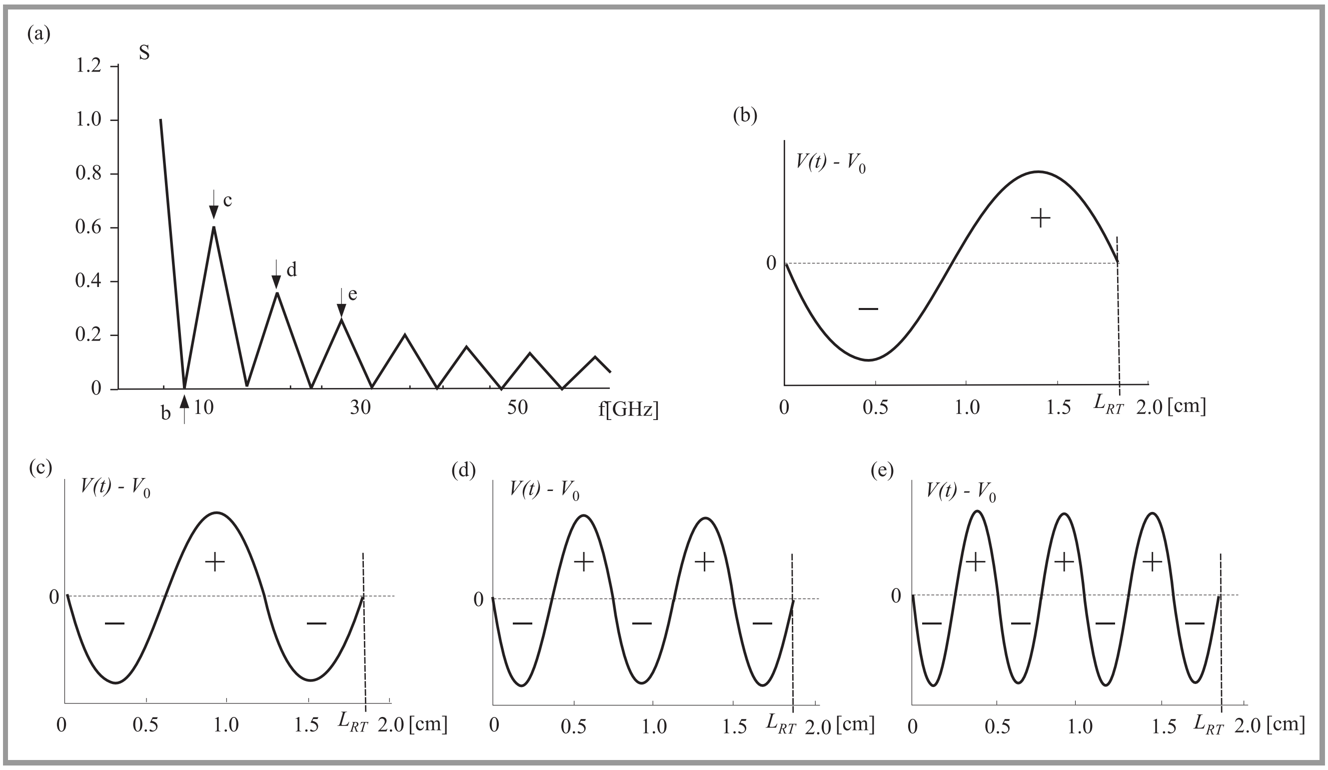

Fig. 4. The dependence of influence degree S on the frequency of applied MW field at the full coverage of the metallic electrode at $\varphi = 0^0$ (a); the distributions of optical wave velocity discrepancy along the microresonator at the point of the first zero interaction $f = \Delta f_{FSR} = 7.77$ GHz (b), at the points of maximal interactions: 11.65 GHz, 19.41 GHz and 27.18 GHz – correspondingly (c), (d), (e).

takes place during the round-trip of the optical wave when one or some wavelengths of MW field can be placed.

At the frequencies of MW field multiple to the fundamental frequency of the microresonator $f_m = \frac{1}{\tau_{RT}}$ full cancelation in variation of the speed of optical wave along the round-trip takes place. Here $t_{RT} = 2L_{FP}\frac{\sqrt{\varepsilon}}{c}$ is the time of a round-trip of optical wave in the microresonator at the absence of external MW field. As the fundamental frequency f_m is equal to the microresonator's free spectral range (FSR) $\Delta f_{FSR} = \frac{c}{2L_{FP}\sqrt{\varepsilon}}$, the periodicity of zero electro-optical interactions is equal to the integral number of Δf_{FSR}.

As the phase velocity of light is changed in accordance with Eq. (1), then it is reasonable to compute the value S that is the result of summation of positive and negative inputs of influence of MW field on the speed of light within the microresonator along the round-trip:

$$S = \left| \int_0^{2L_{FP}} \left(V(t) - V_0\right) \cdot dl \right|, \tag{2}$$

where $V_0 = \frac{c}{\sqrt{\varepsilon}}$.

It is reasonable to call this value S as an influence degree of MW field on optical wave in the microresonator. In Fig. 4a the dependence of the value of influence degree S on the frequency of MW field for the microresonator with the distance between mirrors $L_{FP} = 9.106$ mm and full coverage of the top metallic electrode is presented.

The first zero of waves' interaction takes place at $f = 7.77$ GHz, which corresponds to the fundamental mode of the microresonator $f_m = \Delta f_{FSR}$. The peaks of maximal interactions have a strong periodicity according to the law $\frac{2m+1}{2} \cdot \Delta f_{FSR}$, where $m = 1, 2, 3\ldots$. With the increase of the frequency of MW field the influence degree S decreases, that is stipulated by decrease of non-compensated contribution of the change of the speed of optical wave during the round-trip (Fig. 4c–e). The obtained periodicities for the frequencies of zero and maximal interaction of waves are in an agreement with the corresponding data for microdisk resonator [3]–[7]. The effect of increase of operating frequencies of F-P electro-optical modulator with the decrease of the length of the top metallic electrode is also obtained [20]. The steps of frequencies are also in an agreement with the data for microdisk resonators [3]–[7].

3. Conclusion

The idea to transfer intermediate frequency of MW superheterodyne receiver in optical range is considering now as fruitful and prospective solution for different types of receivers [21]. By this operation it is not only possible completely to get rid of parasitic radiation in RF range, but also attain the high sensitivity, selectivity and bandwidth, while having immunity to the external electromagnetic stray radiation, small size, weight and power consumption [3]–[7], [11]–[14], [21].

Realization of this idea is relying strongly on construction of EOM providing effective interaction of MW electrical signals with optical wave. This key element of MW photonic receiver up to now is $LiNbO_3$ microdisk resonator, which not only needs precise microdisk preparation, but also optical wavelength scale positioning of microprism for light input/output from the microresonator.

An application of high Q-factor F-P microresonator instead of microdisk has been suggested recently [16], [20], that is prospective due to elimination of microprism from construction and application of planar structure instead of circular one.

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