Optics Communications 392 (2017) 114–118

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Silicon based mechanic-photonic wavelength converter for infrared photo-detection

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ARTICLE INFO

Keywords:
Nanorods
Silicon
Photo-detector
Infrared sensor

ABSTRACT

In this paper we present a new concept to realize a mechanic-photonic wavelength converter in silicon chip by construction of nanorods and by modulating the input illumination at temporal frequency matched to the mechanic resonance of the nanorods. The use case is to realize an infrared photo detector in silicon which is not based on absorption but rather on the mechanical interaction of the nanorods with the incoming illumination.

1. Introduction

The development of optical circuits being integrated on silicon (Si) chips has become an important research field in telecommunication technology in the last decade. Silicon has long been is the main platform in electronics but it is also an excellent material for use in photonics due to its good optical, thermos-dynamical and mechanical properties. In addition, wide range of semiconductor fabrication techniques that were developed for Si can be utilized for fabrication of Si nano-photonic devices. High refractive index of Si allows fabrication of high-Q (Finesse) nano cavities and low-loss waveguides.

However, Si is not an efficient material in terms of telecom-light detection since it does not absorb light at wavelength above 1 μm. Various approaches have been proposed to overcome this problem, for example: two-photon absorption [1–3], internal photoemission effect [4–6], thermal nonlinear effect [7–9] and sub-band gap photo-effect [10–12]. However, the quantum efficiency of the listed methods is still relatively low. Moreover, most of the above mentioned approaches have very high noise level due to generation and recombination of electron-hole pairs.

In this work, we present a novel idea of mechanical-photonic wavelength converted (MPWC) in Si which can be used as an infrared detector that is not based upon absorption. The device is designed for the conversion of amplitude modulated infrared wavelength of incidence into a different reference wavelength having the same amplitude modulation while this reference wavelength is below 1 μm and thus can be measured by Si detector.

The MPWC utilizes an optical gradient force induced on Si nanorod by electromagnetic field of incident illumination. When infrared beam is focused by a lens on a surface filled by such Si nanorods, then the photonic gradient force, which is directed laterally, leads to mechanical bending of the nanorod. Because the gradient force is independent of the wavelength, the sensitivity of the MPWC in all the spectral range of near and far infrared can be expected to be almost same.

Because the optical gradient force is very small, usage of the resonant properties of the nanorods is needed. The response time of the resonant systems is larger than of non-resonant one. But the resonant frequency of the nanorod is very large due to their small size and the high elastic modulus of Si. Therefore good response time of the MPWC can be achieved. For utilization of the resonant properties of the nanorod, we propose to modulate the incident wave by a global shutter with frequency equal to the resonant frequency of the nanorods.

Note that optics communication is not an attractive application for our detection concept and it is also not the application this paper is aiming for. In optics communication the detectors are single pixel detectors and they work around the optical wavelength of 1550 nm. What we are aiming for in our paper is to construct a camera, with an array of detectors as the one described in the sections below and to be able to have an imaging camera realized on silicon (and thus all the relevant electronics circuitry are inside and can be integrated with the sensing area) and to have it operated in infrared. In imaging applications when we talk about infrared we do not refer to 1550 nm as in optics communication but rather to 3–5 and 8–12 μm since those are the atmospheric spectral transmission windows. Note also that the alternative to imaging sensors working at 3–5 and 8–12 μm is very expensive. The high quality sensors are cooled sensors and their cost is very high. In the concept that we present in this paper we overcome this problem and allow realizing the detection array on a silicon chip being integrated with the required image processing electronics.

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http://dx.doi.org/10.1016/j.optcom.2017.01.044
Received 22 November 2016; Received in revised form 3 January 2017; Accepted 24 January 2017

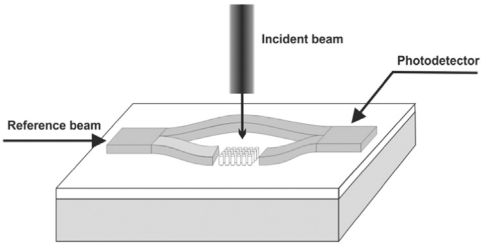

Fig. 1. Schematic sketch of the device.

2. Technical description

Thus as described above, the proposed research aims to develop a hyper-spectral detector realized on a silicon wafer. The operation principle involves a reference beam sent through a waveguide fabricated on top of the wafer at wavelength that can be absorbed by silicon (below 1000 nm). The light passes through a region with special nanorods and reaches a Si photodetector. The incident beam illuminates the nanorods structure region in perpendicular to the surface of the wafer. The arriving incident light can be at any wavelength. Due to the gradient force (photonic momentum) being applied on the nanorods they deform and this deformation affects the phase of the reference light arriving to the photodetector. This phase modulation can be extracted via an optical interferometer configuration seen in Fig. 1. However, the deformation is extremely small. In order to obtain sufficient sensitivity we place a global shutter at the aperture of the imaging lens of the proposed hyperspectral imager. The shutter operates at frequency of e.g. 11.3 MHz that is matched to the mechanical resonance of the nanorods (the mechanical resonance depends on the physical dimensions of the nano rods). Due to this, the deformation is amplified by many orders of magnitude as the rods vibrate at their mechanical resonance and since they have very high Q factor. The schematic sketch of a single pixel of the proposed hyperspectral imager is depicted in Fig. 1. An array of such pixels will form the focal plane array of the proposed hyperspectral imager.

The main advantages of the proposed concept is that it has sensitivity to wide band spectral range; it has sensitivity at all possible wavelengths; it has capability to do dynamic range adaptation and AGC (automatic gain control) in an optical way by changing the intensity of the reference beam; the operation principle of the proposed photodetector uses linear effect (harmonic oscillation of nanorod) and therefore no quantization noise, and low level signal can be detected. The unit is fully analog. When the energy of the incident signal is very small (less than the bandgap of the photodiode), the corresponding bending of the nanorods still occurs. High power signal arriving to the photodiode can be obtained due to the high power of the reference wave. Therefore, the sensitivity of the detector can be much larger than the sensitivity of regular semiconductor photodetectors. This fact can be usable in various fields in which the signal to be sensed are very small as e.g. in astronomy measurements.

3. Simulations

The operation principle being described above has been intensively explored and a thorough physical/mathematical modeling was constructed. The modeling we performed is as follows: Each rod has length l, radius r, and mass $m=\rho F_0$, where ρ is the density of the rod's material and $F_0=\pi r^2$ is its cross section area. It is known, from theory of oscillations that the main differential equation of a bent rod is [13]:

$$EJ\frac{\partial^2 y}{\partial x^2} = M; \tag{1}$$

while y is the bending amplitude and

$$\frac{\partial^2 M}{\partial x^2} = q \tag{2}$$

where J is the moment of inertia which has the following expression for rod with circular cross section [14]:

$$J = \frac{\pi r^4}{4} \tag{3}$$

with E=1.89·10^{10} Pa is the Young's modulus of silicon, $M=M(x, t)$ is the bending moment and q is the intensity of distributed load. After proper mathematical simplification we obtain the full solution to the differential equation obtained by assuming time and space variables separation: $y(x,t)=X(x)T(t)$ which results with:

$$y(x,t) = \frac{P_0}{\alpha^3 EJ}\cdot\frac{K_3(\alpha x)K_2(\alpha x) - K_4(\alpha x)K_1(\alpha x)}{K_2(\alpha x)K_4(\alpha x) - K_1^2(\alpha x)}\cdot\sin(pt) \tag{4}$$

where $\alpha = \sqrt[4]{mp^2/EJ}$, and p is a frequency of forced oscillations of the rod. K_1, K_2, K_3, and K_4 are the Krylov's functions [15]. As an example, in the case of natural frequencies of bending oscillations of the nanorod, the differential equation can be simplified to:

$$\frac{dX(x)^{(4)}}{dx^{(4)}} - \frac{m\omega^2}{EJ}X(x) = 0 \tag{5}$$

where ω is the angular natural frequency. Solving the differential Eq. of (5) with the right boundary conditions leads to:

$$ch(kl)\cos(kl) + 1 = 0 \tag{6}$$

wherein $k^4 = m\omega^2/EJ$. Each real solution magnitude $k_n l$ corresponds to a value of natural frequency of the rod ω_n [16]. The first four values of this solution are:

$$k_1 l = 1,875;\ k_2 l = 4,694;\ k_3 l = 7,885;\ k_4 l = 10,966; \tag{7}$$

and those are the corresponding natural frequencies of bending oscillations of the nanorod:

$$\omega_1 = \lambda\left(\frac{1,875}{l}\right)^2;\ \omega_2 = \lambda\left(\frac{4,694}{l}\right)^2; \tag{8}$$

where the constant λ is given by the following expression:

$$\lambda^2 = \frac{EJ}{m} = \frac{EJ}{\rho F_0} \tag{9}$$

where the length (height) of the nano rod is l, Young's modulus (elasticity) of silicon is E, the moment of inertia cross section is J, the cross-sectional square of the nano rod is F_O and the mass per unit length (distributed) of the nanorod is m.

The developed analytical equations were simulated by Matlab. The simulation result is seen in Fig. 2. Only the spectral position of the peak is important. The displacement value is not precise. The obtained peak's position is 11.295 MHz.

In the left side of Fig. 3 we show the simulations obtained when using industrial software called Comsol to solve the relevant heat and propagation equations and to compare its output with the result obtained by the Matlab simulations simulating the analytical modeling that we have developed. In the right part of the figure we present the Q factor versus the oscillating frequency which gives an estimation of the quality of the obtainable resonance.

In Fig. 4 we show the results obtained when performing the Comsol simulations at the resonance frequency and away from this frequency. Obviously the displacement amplitude of the nano rods is significantly modified.

The position of the resonance frequency is 11.304 MHz which is very close to the frequency we received in the Matlab simulation. Thus, one may see that good agreement existing between the analytical simulation shown in Fig. 2 and the results obtained from Comsol (Fig. 4).

The resonant amplitude can be evaluated by multiplication of the non-resonant amplitude that we obtained as 1.5E-13 m with the