Conference materials
UDC 681.782.473
DOI: https://doi.org/10.18721/JPM.163.214

Modelling the influence of planar waveguide cladding thickness on the absorption efficiency of a superconducting NbN strip

N.A. Vovk[1]✉, M.V. Shibalov[2], A.M. Mumlyakov[2], Ju.P. Korneeva[2], I.M. Asharchuk[2], K.V. Smirnov[1], M.A. Tarkhov[2]

[1] National Research University Higher School of Economics, Moscow, Russia;

[2] Institute of Nanotechnologies of Microelectronics of the RAS, Moscow, Russia

✉ vovkolg2011@gmail.com

Abstract. This paper reports simulation results for 1550 nm wavelength absorption efficiency of a superconducting NbN nanowire coupled to a single-mode Si_3N_4 waveguide depending on SiO_2 cladding thickness. Simulation results for straight, U- and W-shaped strips show that with perfect planarization (no top cladding) the absorption coefficient per unit length is 0.031, 0.07 and 0.11 dB/μm, respectively.

Keywords: CMP, cladding, superconducting, detectors

Funding: 1021061509690-0-1.2.1

Citation: Vovk N.A., Shibalov M.V., Mumlyakov A.M., Korneeva Ju.P., Asharchuk I.M., Smirnov K.V., Tarkhov M.A. Modelling the influence of planar waveguide cladding thickness on the absorption efficiency of a superconducting NbN strip, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.2) (2023) 87–91. DOI: https://doi.org/10.18721/JPM.163.214

Материалы конференции
УДК 681.782.473
DOI: https://doi.org/10.18721/JPM.163.214

Моделирование влияния толщины буферного слоя планарного волновода на эффективность поглощения сверхпроводящей NbN полоской

Н.А. Вовк[1]✉, М.В. Шибалов[2], А.М. Мумляков[2], Ю.П. Корнеева[2], И.М. Ашарчук[2], К.В. Смирнов[1] , М.А. Тархов[2]

[1] Национальный исследовательский университет «Высшая школа экономики», Москва, Россия;

[2] Институт нанотехнологий микроэлектроники РАН, Москва, Россия

✉ vovkolg2011@gmail.com

Аннотация. В данной работе представлены результаты моделирования эффективности поглощения на длине волны 1550 нм сверхпроводящей нанополоской NbN, интегрированной с одномодовым волноводом Si_3N_4, в зависимости от толщины буферного слоя SiO_2. Результаты моделирования для прямых, U- и W-образных полосок показывают, что при идеальной планаризации (без верхнего буферного слоя) коэффициент поглощения на единицу длины составляет 0,07 ,0,031 и 0,11 дБ/мкм соответственно.

Ключевые слова: ХМП, буферный слой, сверхпроводник, детектор

Финансирование: 1021061509690-0-1.2.1

Ссылка при цитировании: Вовк Н.А., Шибалов М.В., Мумляков А.М., Корнеева Ю.П., Ашарчук И.М., Смирнов К.В. Моделирование влияния толщины буферного слоя планарного волновода на эффективность поглощения сверхпроводящей NbN полоской // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.2. С. 87–91. DOI: https://doi.org/10.18721/JPM.163.214

Introduction

Planarization technology of multilayer CMOS structures is one of the key steps in nano- and microelectronics manufacturing. Without planarization, each successive layer applied follows the topology of the previous layers, creating undesirable steps and steep slopes on the surface of the new layer, which degrades its performance. Photonic integrated circuits (PIC), used for converting optical signals into electrical signals, are multilayer structures comprising such basic elements as waveguides, electro-optical modulators, photon detectors and quantum emitters [1]. The main element for planarization of such circuits is the waveguide cladding layer, on which the control and detection elements of radiation are placed. One of the practical implementations of cladding planarization technology in PICs is the creation of a multi-resonator structure and vertical inter-wavelength coupling [2]. Modern CMP (Chemical Mechanical Planarization) equipment has high precision processing, which allows not only to thin cladding but also to prepare the surface for further technological operations, e.g., for splicing wafers with SiO_2 cladding and $LiNbO_3$ electro-optical modulator [3].

Integrating the detector onto the upper cladding reduces the number of standard processing steps, such as etching process, spin coating photoresist, that modify the waveguide surface and the result in the losses increase in the entire optical system. Similarly, if the waveguide is etched after the detector has been fabricated, the possibility of the detector itself being modified by technological operations can be excluded.

Ideally, the planarization of the upper cladding to the Si_3N_4 surface would allow the detector to be placed on the waveguide itself, but due to different material planarization rates, recesses are formed in the Si_3N_4, which degrades the surface and increases the roughness of the waveguide [4]. Due to the planarization rate of the PECVD SiO_2 layer, which varies from 1 nm/s to 2 nm/s, one cannot exclude a situation where a small thickness of the upper cladding will remain on the surface of the waveguide, which greatly affects the radiation detection efficiency.

In this paper, we calculate the effect of the residual SiO_2 cladding layer after planarization process [5] on the efficiency of pulling an evanescent wave from a Si_3N_4 waveguide by a superconducting NbN nanostrip.

Materials and Methods

The first step in PIC design is to determine the compatibility of the operating wavelength with the waveguide material. At the telecommunication wavelength of 1550 nm, Si_3N_4-based platforms (refraction index $n = 2.01$) exhibit record low optical absorption [6]. To localize the optical mode of radiation in the Si_3N_4 waveguide, a cladding layer with a lower refractive index, SiO_2 ($n = 1.44$) is used.

We consider a single-mode radiation propagation with a wavelength of 1550 nm, which is defined by the geometry of the waveguide cross section of 1×1 μm². As a superconducting material, NbN, which is widely used for single-photon detectors [7], is chosen. NbN refractive index at 1550 nm is 5.23–5.82i, where the multiplier of the imaginary part is responsible for light absorption by the material.

The transmittance characteristic of a planar waveguide is defined as $\ln(P_{out}/P_{in})$, where P_{out} is the output signal power, P_{in} is the input signal power. And according to the Boeger–Lambert–Bera law considering the superconducting strip as an absorbing medium, the transmittance is defined as:

$$-\alpha \cdot L_{NbN} = \ln\left(\frac{P_{out}}{P_{in}}\right), \quad (1)$$

where L_{NbN} is the strip length, α is the absorption coefficient.

An alternative way to calculate the absorption index is an analytical formula that includes the effective refractive index n_{eff}, which determines the phase velocity of the surface wave in the waveguide, taking into account the integrated detector:

$$\alpha = -20\lg\left(e^{-\frac{2\pi \cdot \, imag\left(n_{eff}\right) \, L_{NbN}}{\lambda}} \right), \qquad (2)$$

where $imag(n_{eff})$ is the imaginary part of the effective refractive index of the strip waveguide, λ is the operating wavelength.

The absorption of light by the detector is determined by the area of wave mode overlap with the superconducting strip, but there are limits to the width of the strip used. Since the most common superconducting device implementation is based on a superconducting nanowire with 50–100 nm width patterned from a thin film (thickness 5–10 nm), we use the width of the strip equal to 100 nm, the gap is 50 nm and the thickness is 5 nm. For the better absorption of electrical transverse TE-like modes, in order to decrease the detector length, a U-shaped and W-shaped meander can be used as an alternative to a single long strip.

Simulations are performed for different strip configurations (Fig. 1): a single strip (Fig. 1,*a*), a strip with one turn (U-shape) (Fig. 1,*b*) and a strip with two turns (W-shape) (Fig. 1,*c*).

Results

The simulation was performed in COMSOL Multiphysics software in the Electromagnetic Waves, Beam Envelopes (EWBE) physics section using the finite element method. The perfect electric conductor condition was used as the boundary conditions for the entire modelling scope, except for the input and output ports. The 2D cross section modelling of the waveguide gives the distribution of the optical mode field considering the integrated detectors and the residual cladding thickness. The simulation results are the values of the effective refractive index n_{eff}, which $imag(n_{eff})$ (Fig. 1,*d*) imaginary parts can be used to calculate the absorption index according to Eq. (2).

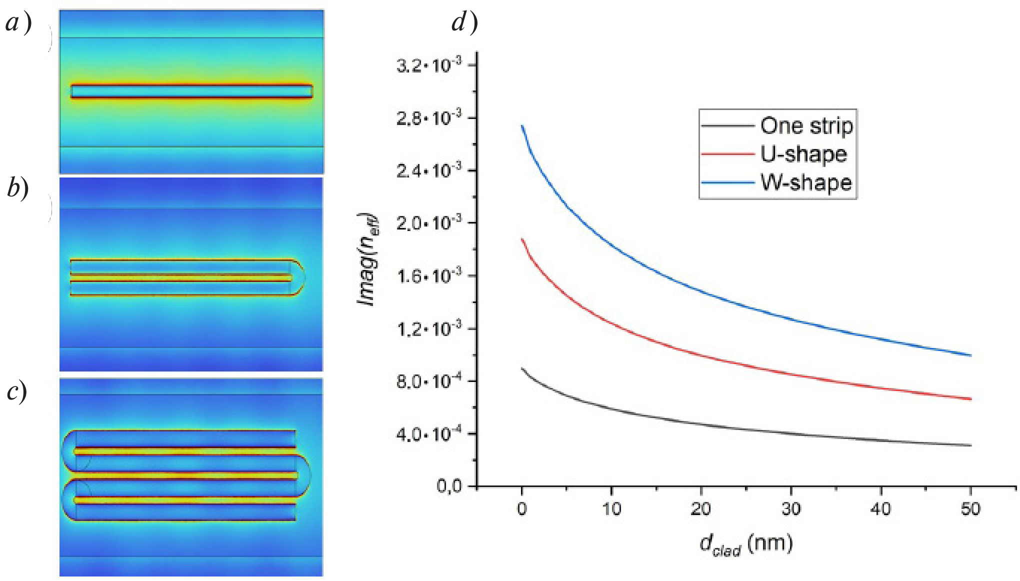

Fig. 1. 3D simulation of the absorption intensity for the radiation mode in waveguide with: NbN single strip (*a*), NbN strip with one turn (U-form shape) (*b*) and NbN strip with two turns (W-form shape) (*c*). The panel in (*d*) shows the imaginary part of the effective refractive index in the waveguide with a detector of various configurations as function of the thickness of the upper SiO_2 cladding calculated by Eq. (2)

Fig. 2 shows 3D simulation results demonstrating the effect of the thickness of the upper cladding of the waveguide, which varied between 0 and 50 nm on the trapping of the NbN evanescent wave by a 36 μm long strip, a 25 μm long U-shape strip and an 18 μm long W-shape strip. For given strip configurations and geometrical sizes with perfect planarization (d_{clad} = 0 nm) maximum absorption coefficients are 28% for straight strip, 44% for U-shape and 49% for W-shape strip, which gives absorption coefficient of 0.031 dB/μm, 0.07 dB/μm and 0.11 dB/μm per 1 micron length for above mentioned topologies, respectively.

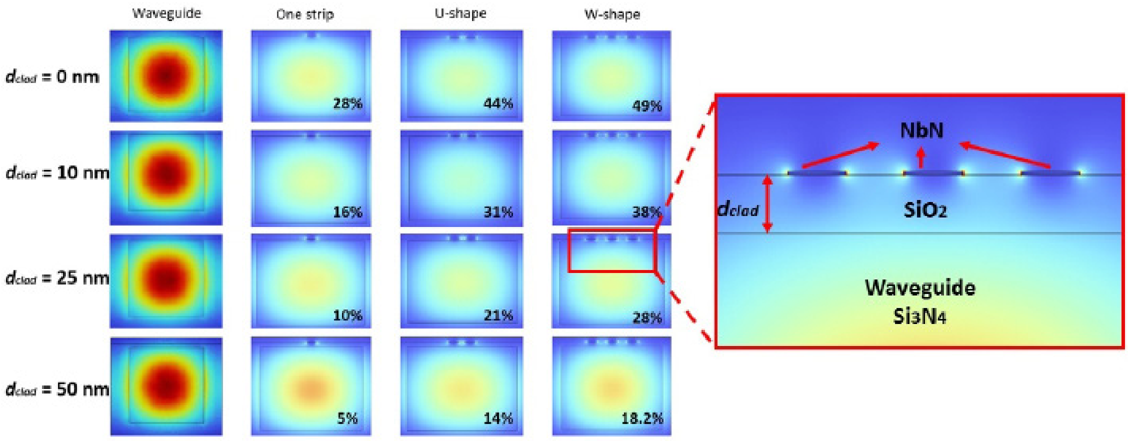

Fig. 2. Simulation results of optical power distribution in a planar waveguide with different shapes of NbN strip at different thicknesses (d_{clad}) of the cladding layer. The zoom shows the topology of the detector with a waveguide

The electric field intensity decreases exponentially at the waveguide boundary as the upper cladding increases, which leads to decrease in the overlap integral of the propagating mode and the detector. Fig. 3 shows the simulation results, which allow one to choose required length of the detector strip to achieve 99% absorption of the input radiation, depending on the type of detector topology and the thickness of the residual upper SiO2 cladding. With an upper cladding thickness of 50 nm SiO_2 to achieve full internal absorption, the length of one strip should be 400 μm, for U-type topology the length of each strip should be 186 μm, for W-type topology 123 μm. The choice of a compact W-type detector topology guarantees a combination of high detection efficiency and small footprint in the PIC.

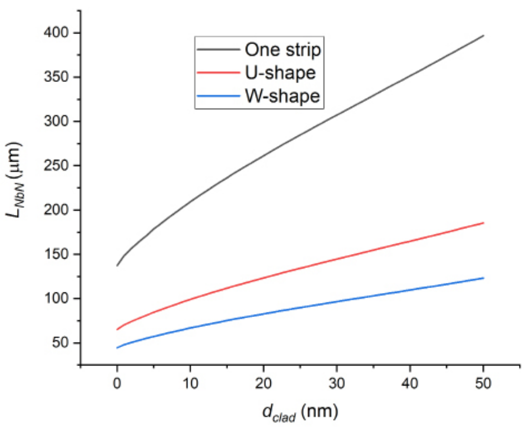

Fig. 3. Length of NbN detector strips of different topology, providing 99% absorption of waveguide radiation, as function of the upper cladding thickness

Conclusion

In this work the dependence of waveguide mode absorption by a superconducting NbN strip of different topology on the thickness of waveguide cladding after technological planarization operation is demonstrated. Simulation results allowed determining absorption efficiency per 1 μm length of superconducting NbN strip of different configuration. The proposed calculation can be used to design a single photon detector, matched to a single-mode waveguide, based on NbN strip, whose length determines 99% absorption efficiency, with a fixed thickness of waveguide cladding. Such a detector is used in quantum computing and quantum cryptography applications.

Acknowledgments

The work was supported by project 1021061509690-0-1.2.1. Ministry of Education and Science of the Russian Federation.

REFERENCES

1. **Elshaari A., Pernice W., Srinivasan K., Benson O., Zwiller V.,** Hybrid integrated quantum photonic circuits, Nature Photonics. 14 (5) (2020) 285–298.
2. **Dooyoung Hah,** Analysis of optical gyroscopes with vertically stacked ring resonators, Turkish Journal of Electrical Engineering and Computer Sciences; 29 (3) (2021) 1554–1564.
3. **Ghosh S., Yegnanarayanan S., Ricci M., Kharas D., Juodawlkis P.,** Low-loss Thin Film Lithium Niobate Bonded on Silicon Nitride Waveguides, 2020 Conference: CLEO: Science and Innovations 2020.
4. **Ye Z., Jia H., Huang Z., Shen C., Long J., Shi B., Luo Y., Gao L., Sun W., Guo H., He J., Liu J.,** Foundry manufacturing of tight-confinement, dispersion-engineered, ultralow-loss silicon nitride photonic integrated circuit, Photonics Research. 11 (4) (2023) 558–568.
5. **Pfeiffer M.H.P., Herkommer C., Liu J., Morais T., Zervas M., Geiselmann M., Kippenberg T.J.** Photonic Damascene Process for Low-Loss, High-Confinement Silicon Nitride Waveguides, IEEE Journal of Selected Topics in Quantum Electronics. 24 (4) (2018).
6. **Heck M., Bauters J., Davenport M., Spencer D., Bowers J.,** Ultra-low loss waveguide platform and its integration with silicon photonics, Laser & Photonics Reviews. 8 (5) (2014) 667–686.
7. **Kahl O., Ferrari S., Kovalyuk V., Goltsman G., Korneev A., Pernice W.,** Waveguide integrated superconducting single-photon detectors with high internal quantum efficiency at telecom wavelengths, Scientific Reports. 5 (11) (2015) 1–11.

THE AUTHORS

VOVK Nikolay A.
vovkolg2011@gmail.com
ORCID: 0000-0002-8687-3202

SHIBALOV Maksim V.
maxshibalov@gmail.com
ORCID: 0000-0002-5818-4776

MUMLYAKOV Alexander M.
irbit_oppozit@mail.ru
ORCID: 0000-0002-1081-8338

KORNEEVA Julia P.
korneeva_yuliya@mail.ru
ORCID: 0000-0003-1576-265X

ASHARCHUK Ilya M.
ilyaasharchuk@gmail.com
ORCID: 0000-0001-6445-0009

SMIRNOV Konstantin V.
skv2050@mail.ru
ORCID: 0000-0003-1562-0520

TARKHOV Michael A.
tmafuz@mail.ru
ORCID 0000-0001-8168-1917

Received 09.07.2023. Approved after reviewing 17.07.2023. Accepted 24.07.2023.