photonics

IMPACT FACTOR 2.4

CITESCORE 2.3

Communication

Multispectral SNSPD Using a Modified Distributed Bragg Reflector, Gold Mirror, and Multilayer-Nanowire Structures

Ping-Han Wu, Hsin-Yeh Wu and Stathes Paganis

MDPI

https://doi.org/10.3390/photonics10101142 *photonics*

Communication

Multispectral SNSPD Using a Modified Distributed Bragg Reflector, Gold Mirror, and Multilayer-Nanowire Structures

Ping-Han Wu [1,*], Hsin-Yeh Wu [2,3] and Stathes Paganis [2,3]

[1] Kang Chiao International School, New Taipei 231049, Taiwan
[2] Leung Center for Cosmology and Particle Astrophysics, National Taiwan University, Taipei 10617, Taiwan
[3] Department of Physics, National Taiwan University, Taipei 10617, Taiwan
* Correspondence: s10232@kcis.com.tw

Abstract: A multispectral superconducting nanowire single-photon detector (SNSPD) that is sensitive to different incident photon wavelength bands, is proposed. The SNSPD consists of a distributed Bragg reflector (DBR), a gold mirror, and two regions employing four NbN nanowire meander layers. Using the DBR, both as a filter and a reflector, creates two distinct detection bands. The first detection band has a peak absorptance of 0.792 at a wavelength of 1164 nm, while the second band has a total absorptance of >0.70 in the wavelength range 1440 to 2000 nm. The design of the proposed SNSPD can be tuned to provide sensitivity to different wavelength bands. While conventional SNSPDs do not typically provide photon wavelength sensitivity, the band-selection design proposed in this work opens up its potential applications for future quantum communication technology.

Keywords: SNSPD; multispectral; dual-spectral; single-photon; quantum communication

1. Introduction

As an ideal detector for photons with weak optical power, superconducting nanowire single-photon detectors (SNSPDs) have numerous emerging applications, including, but not limited to, quantum key distribution [1,2], deep space communication [3], single-photon lidar systems [4], and mass spectrometry [5]. Since the first SNSPD was demonstrated in 2001, which exhibited low system detection efficiency (SDE) [6], researchers have made substantial strides toward overcoming limited SDE by employing different optical cavity designs. Highly efficient SNSPDs have been developed primarily through the use of metallic [7,8] or dielectric mirrors [9,10]. These developments have contributed to the realization of SNSPDs with near-unity detection efficiencies at certain target wavelengths. Nevertheless, many reported detectors are still limited in terms of bandwidth, exhibiting high SDE across a bandwidth of typically a few hundred nanometers around a single resonant wavelength, preventing SNSPDs from fully exploiting the potential of broader wavelength ranges. To extend the detection bandwidth, recent efforts in developing broadband or multispectral SPSNDs have taken advantage of multiple optical absorption resonances [11,12] or multilayer-nanowire structures [13–15], thus extending the detection bandwidth, and providing solutions for a wider range of applications, such as fluorescence correlation spectroscopy [16], singlet oxygen luminescence detection [17], as well as ranging and imaging [18,19].

Despite many recent efforts to create broadband or multispectral SNSPDs, current designs exhibit limited photon wavelength sensitivity because the voltage pulse pattern of the detector is insensitive to variations of incident single-photon wavelengths. To address the limited-photon-wavelength-sensitivity problem in existing multispectral or broadband SNSPD designs, we present a dual-spectral SNSPD that can detect incident single photons at two well-separated detection bands with high NbN nanowire absorptance. By stacking a distributed Bragg reflector (DBR) designed to target wavelengths between 1070 and 1400 nm on a gold mirror and placing all four layers of NbN nanowires at

Citation: Wu, P.-H.; Wu, H.-Y.; Paganis, S. Multispectral SNSPD Using a Modified Distributed Bragg Reflector, Gold Mirror, and Multilayer-Nanowire Structures. *Photonics* **2023**, *10*, 1142. https://doi.org/10.3390/photonics10101142

Received: 19 September 2023
Revised: 7 October 2023
Accepted: 10 October 2023
Published: 12 October 2023

positions exhibiting strong absorption resonance, a dual-spectral SNSPD is realized. As opposed to previous multispectral SNSPD designs, the detector presented in this work can categorize absorbed photons into either of the two detection bands based on their wavelength. The proposed design holds promise for potential applications in quantum communication, where the differentiation of signals based on varying photon wavelengths may be necessary.

2. SNSPD Design and Materials

The proposed SNSPD design is shown in Figure 1a, and the nanowire meander structure is depicted in Figure 1b. The structure presented contains an alternating SiO_2/TiO_2 DBR, on top of a 200 nm gold mirror serving as the cavity. The design also utilizes a total of four layers of nanowires, for single-photon detection. As shown in Figure 1a, there is one layer of nanowire placed in Region 1 (upper region) and three layers of nanowires stacked in Region 2 (lower region). The nanowire meander in Region 1 is positioned at 4973 nm and the nanowire layers in Region 2 are positioned at 525 nm, 480 nm, and 435 nm, with the reference point being the bottom of the gold layer. Each meandering of NbN nanowire has a thickness of 7 nm, and a width and pitch of 100 nm; all layers, including the dielectric and the gold mirror, are tuned to maximize absorption resonance at the position where the nanowires are placed.

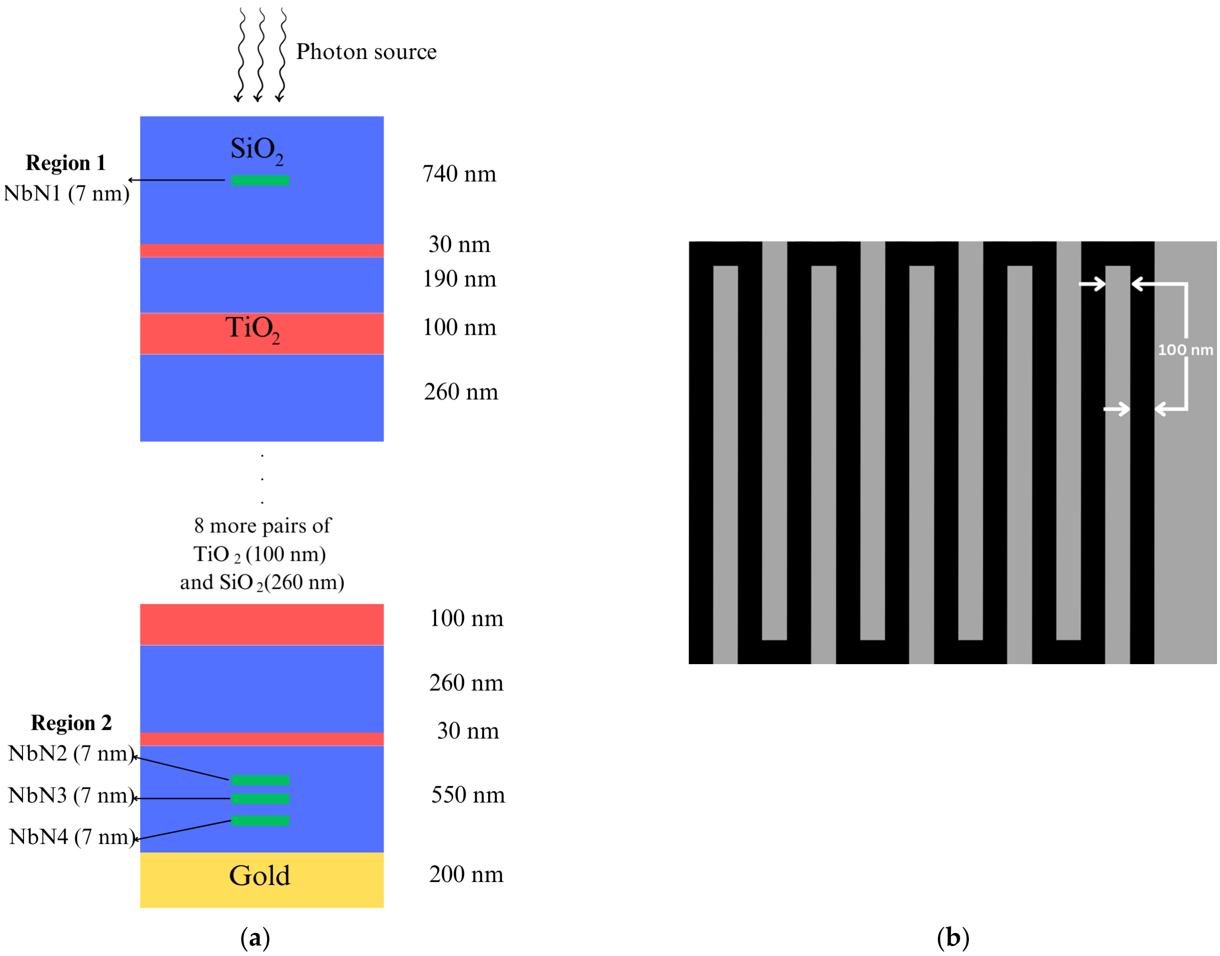

Figure 1. (**a**) Schematic of the simulated structure. Nanowire meander layers are 7 nm thick and have SiO_2 spacers in between one another. In the simulation, the photon source is normally incident upon the structure as shown. In the image, SiO_2 layers are represented by the color blue, TiO_2 layers by red, gold mirror by a yellow, and NbN nanowires by green. (**b**) Dimensions of the simulated nanowire meander structure (thickness of 7 nm and width and pitch of 100 nm).

Superconducting material choice can heavily impact the SDE and characteristics of an SNSPD. In this study, NbN is chosen as the nanowire material due to its high critical temperature, stability through thermal cycling, exceptional mechanical properties (high wear resistance and hardness), and high intrinsic optical absorption within the studied wavelength range.

Ideally, the simulation result should show that the nanowire meander in Region 1 is sensitive to photons with wavelengths of about 1164 nm, while the three layers of nanowires positioned in Region 2 are sensitive to photons with wavelengths within the range of 1440 to 2000 nm.

3. Simulation and Results

The following section outlines the simulation results. To calculate the reflectance of the dielectric stack above the gold mirror, the transfer matrix method was employed. As for electric field intensity and nanowire absorptance calculations, the Ansys Lumerical finite-difference time-domain (FDTD) solver was utilized.

3.1. Band Selection DBR

3.1.1. The Transfer Matrix Method

To calculate the overall reflectance of a DBR, a MATLAB code based on the transfer matrix method must be developed.

For layers with thickness t_i and refractive index n_i, the characteristic matrix can be calculated using Equation (1), where reflectance r and transmittance t are obtained using Fresnel's equations.

$$M_i = \frac{1}{t}\begin{bmatrix} e^{-j\frac{2\pi n_i t_i}{\lambda}} & 0 \\ 0 & e^{j\frac{2\pi n_i t_i}{\lambda}} \end{bmatrix}\begin{bmatrix} 1 & r \\ r & 1 \end{bmatrix}. \quad (1)$$

With n layers of dielectrics, the transfer matrix becomes

$$M_{total} = M_1 M_2 M_3 \ldots\ldots M_n = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}. \quad (2)$$

Reflectance R is then given using

$$R = \left| \frac{M_{21}}{M_{11}} \right|^2. \quad (3)$$

Using the transfer matrix method, it becomes possible to calculate the reflectance of a DBR across a wavelength range.

3.1.2. Modified DBR

The DBR employed in the proposed SNSPD differs from conventional ones, where each layer's thickness is typically set as $\frac{\lambda}{4n}$, with λ being the target wavelength and n representing the real part of the refractive index of the dielectric material employed. Through the utilization of a modified DBR design, where the layers with higher refractive index possess a thickness less than $\frac{\lambda}{4n}$ and layers with lower refractive index have a thickness greater than $\frac{\lambda}{4n}$, together with appropriate adjustments in the thickness of dielectrics within the three initial and final layers, it becomes possible to mitigate the adverse effects of higher-order interference, and high-order modes of constructive interference that cause unwanted spectral ripples in conventional DBR [20,21]. Since the DBR serves both as a mirror and a filter reflecting photons within the 1070 to 1400 wavelength range, while allowing photons with wavelengths > 1400 to pass through, high-order modes of constructive interference must be mitigated to ensure high transmittance in the desired wavelength range. The reflectance–wavelength graphs of a conventional DBR targeting 1230 nm and a modified DBR, with a structure shown in Figure 2a, are depicted in Figure 2b.

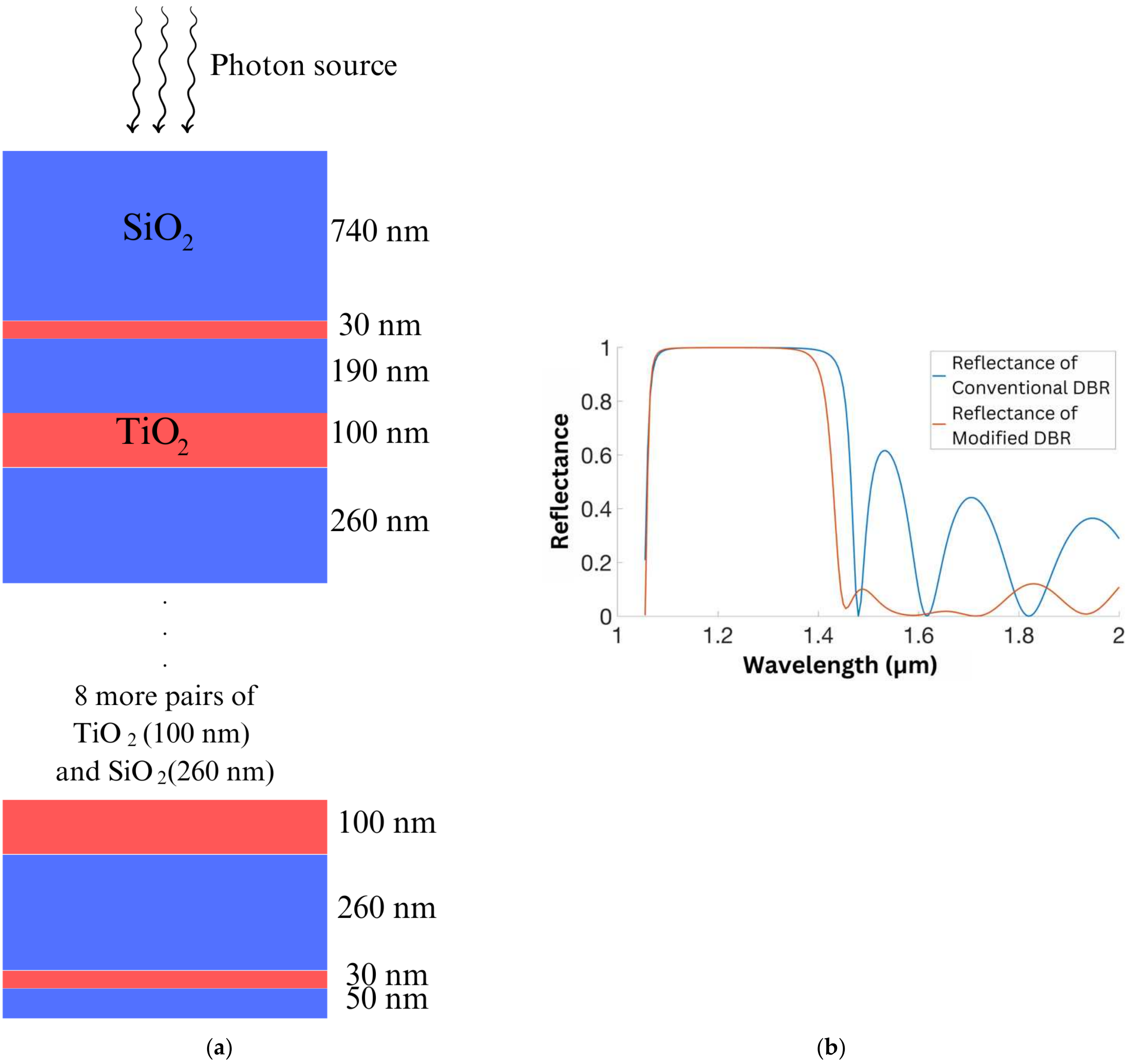

Figure 2. (**a**) Schematic of the simulated modified DBR. In this design, the gold mirror, some of the SiO_2 above the gold mirror, and all layers of the proposed SNSPD's nanowires are removed. (**b**) The reflectance as a function of wavelength for conventional and modified DBR. The modified DBR has a Q-factor of 3.3 (since we target broadband, the Q-factor is not large).

As shown in Figure 2b, the modification does not heavily influence the reflectance in the region near the target wavelength. While the modified DBR's ability to eliminate higher-order interference is compromised with the addition of thick SiO_2 layers and the gold mirror below it, the modified DBR still proves to work better than conventional DBR designs.

With the DBR acting as a mirror and a filter that primarily reflects light with wavelengths ranging from 1070 to 1400 nm, it is possible to create two well-separated absorption bands through the addition of a gold mirror and three layers of NbN nanowires below the DBR. Since gold has high reflectance in the infrared region, it reflects most of the photons passing through the dielectric stack.

3.2. Dual-Band Mirror Using Modified DBR + Gold

In order to identify the optimum position to place the nanowire meanders, the electric field intensity within the dielectrics is calculated, as shown in Figure 3. The electric field colormap demonstrates the principle concept behind a dual-spectral SNSPD. Thanks to the DBR above the gold mirror, most photons with wavelengths ranging from 1070 to 1400 nm are reflected in the first few layers of the dielectric stack.

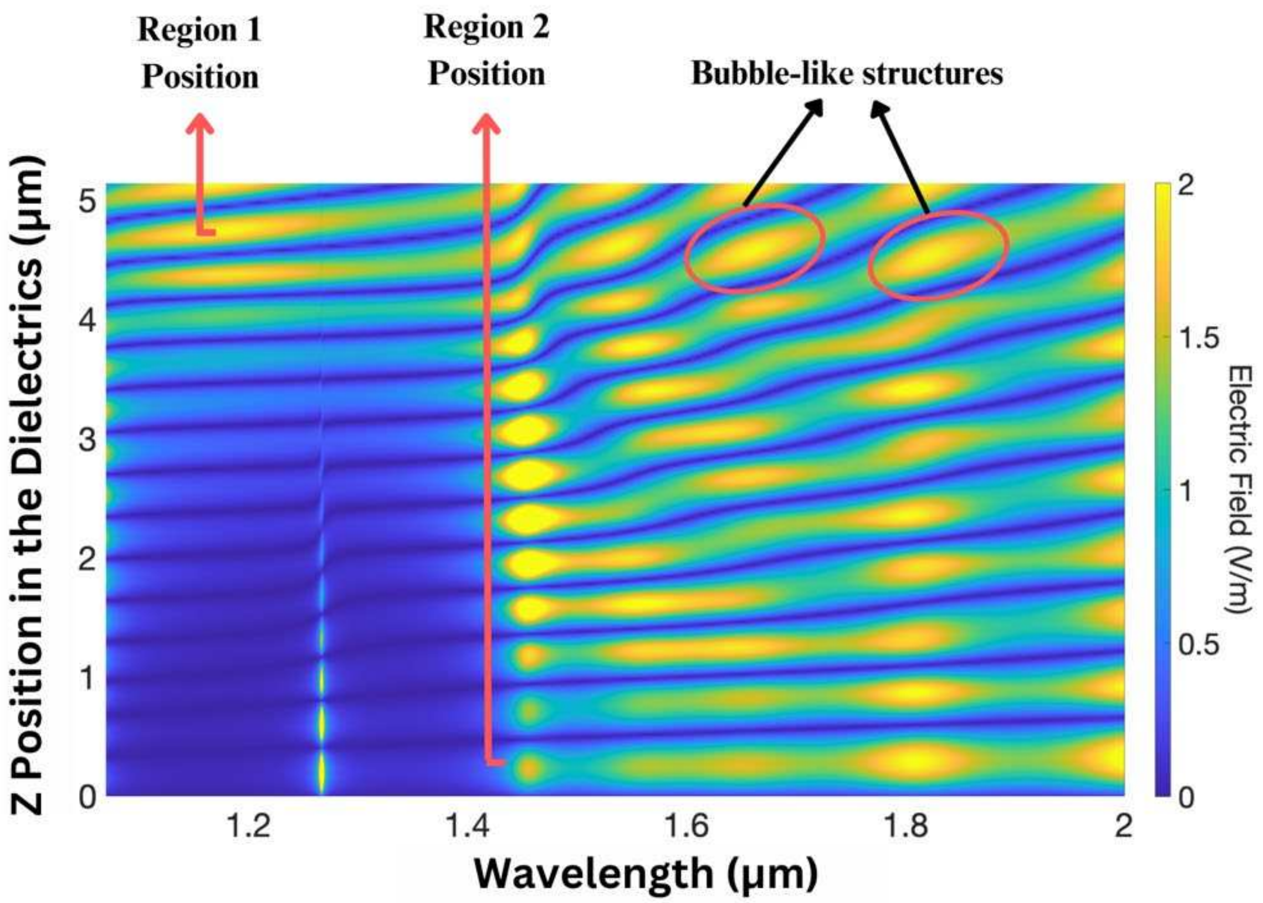

Figure 3. FDTD simulates the electric field intensity profiled using the wavelength and the Z position in the dielectric layers above the gold mirror of the SNSPD. The NbN nanowires are then positioned at places with the strongest electric field intensity. In this colormap, it is obvious that the first few layers of the dielectric stack filtered out most photons with wavelengths from 1070 to 1400 nm before they reached the layers below.

The electric field intensity variation creates bubble-like structures in the colormap due to the interference introduced by thicker layers of SiO_2, such as the layers with thicknesses of 550 nm and 740 nm. At times, the interference pattern introduced by these layers might lead to low nanowire absorption at certain wavelengths. Thus, thicker dielectrics in the SNSPD should be carefully tuned and optimized to the specific desired thickness, maximizing the absorption resonance at the region where the nanowire meanders are placed.

Another point to note in the electric field intensity colormap shown in Figure 3 is that photons with wavelengths > 1400 nm still have considerable electric field strength in multiple layers of the dielectric stack, due to the gold mirror's high reflectance. This effect is one of the limitations of this device. Due to the strong electric field in the uppermost SiO_2 layer, when a NbN nanowire layer is inserted in Region 1, it will also absorb some photons with longer wavelengths. To mitigate this effect, three layers of nanowires are stacked in the SiO_2 layer between the gold mirror and the DBR.

3.3. Dual-Spectral SNSPD

After inserting four layers of NbN nanowire into the structure according to the design shown in Figure 1a. Figure 4 illustrates the absorptance of each nanowire meander.

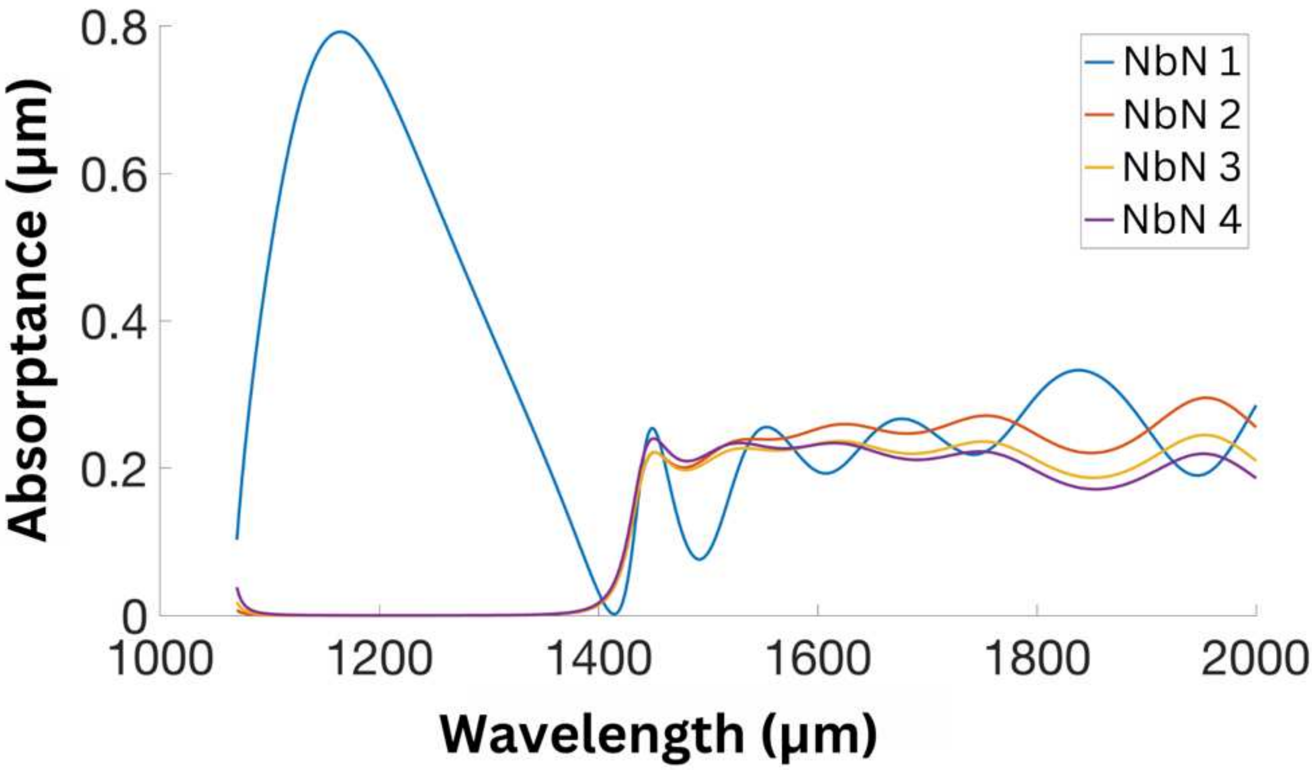

Figure 4. The absorptance of each nanowire is shown. The absorptance of NbN1, or the uppermost nanowire in the SNSPD design, peaks at 1164 nm with a value of 0.792. As for NbN2, the nanowire demonstrates an absorptance > 0.2 for wavelengths from 1438 to 2000 nm. For NbN3, its absorptance is >0.187 for wavelengths from 1438 to 2000 nm. Finally, NbN4 exhibits an absorptance > 0.171 for wavelengths ranging from 1435 nm to 2000 nm.

Note: As shown in Figure 1a, Region 1 (upper region) consists of NbN1, and Region 2 (lower region) contains NbN2, NbN3, and NbN4.

Figure 4 highlights the effect of the DBR, which blocks most photons with wavelengths 1070~1400 nm from reaching nanowires positioned in Region 2. Also, while the DBR employed in this design has high reflectance from 1070 to 1400 nm, since it remains challenging to control the phase dispersion and interference introduced by the dielectric stack [13], the absorption band in the shorter wavelength region is very limited. On the contrary, a gold mirror has not only good reflectance in the infrared region but also ignorable phase dispersion, enabling a relatively constant absorptance for wavelengths from 1440 nm onwards.

Figure 5 shows the total absorptance of nanowire layers placed in Region 1 and Region 2.

From Figure 5, the dual-spectral characteristic of the SNSPD can be readily observed. The nanowire in Region 1 primarily absorbs photons with wavelengths around 1164 nm, and the nanowire layers in Region 2 (NbN2–NbN4) are responsible for absorbing photons with wavelengths from 1440 to 2000 nm.

To demonstrate the effect of the multilayer-nanowire structure, Figure 6 depicts the simulated absorptance when just two NbN nanowire layers are utilized. Figure 6 shows the simulated absorptance of these two nanowire layers in a SNSPD.

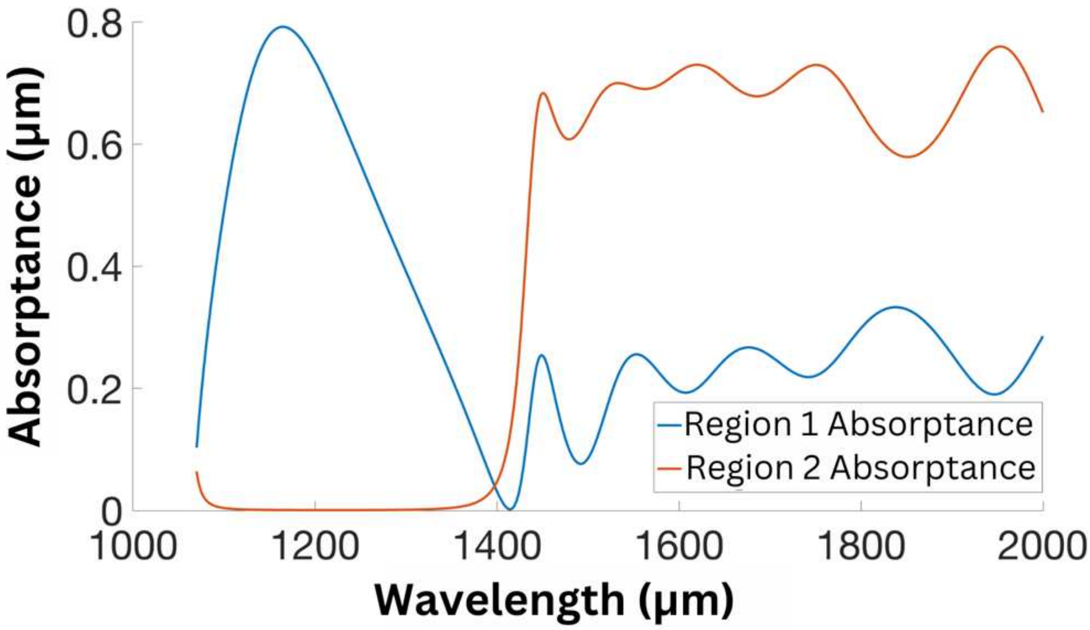

Figure 5. The absorptance of nanowire meanders in Regions 1 and 2 is shown. Region 1 exhibits a peak absorptance at 1164 nm, reaching a value of 0.792, and Region 2 has a total absorptance > 0.579 for all wavelengths ranging from 1440 to 2000. The total absorptance of all 4 layers of nanowires combined demonstrates high SDE.

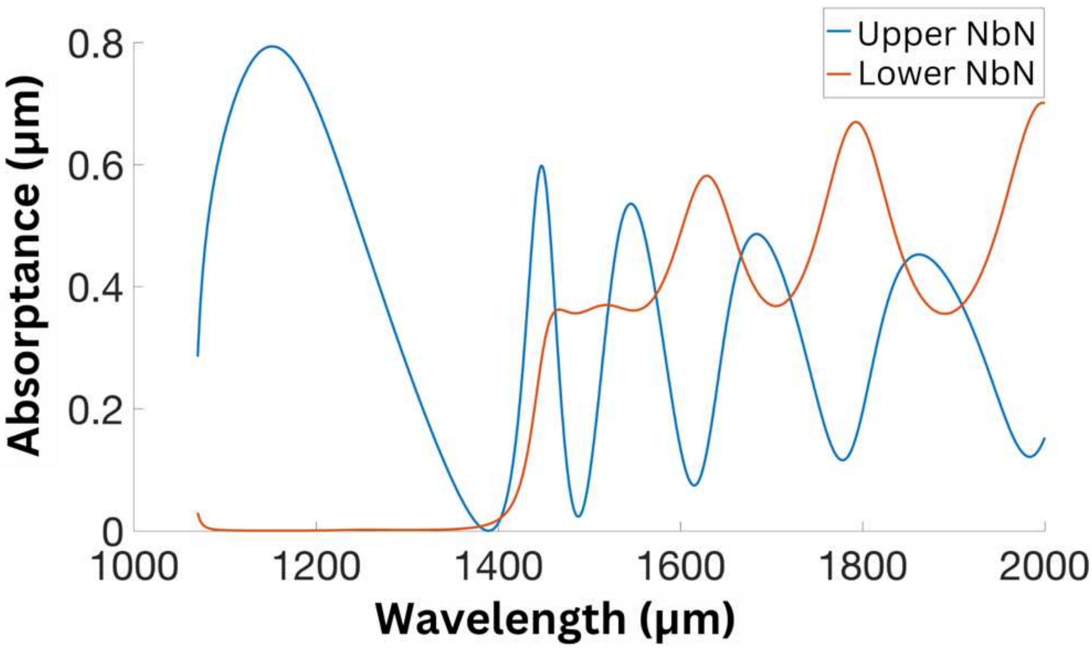

Figure 6. Simulated absorptance of the upper and lower nanowire layers in a SNSPD. The peak absorptance of the upper nanowire layer has a value of 0.794 at the wavelength 1151 nm. The lower-positioned nanowire layer has an absorptance > 0.355 for wavelengths from 1460 to 2000 nm.

After comparing the two absorptance–wavelength graphs in Figure 6 to those in Figure 5, it is evident that the addition of more nanowires in Region 2 successfully decreases the uppermost nanowire's high absorptance at certain wavelengths > 1440 nm; therefore, creating a more desirable dual-spectral SNSPD with the capability to distinguish between photons with wavelengths in distinct absorption bands.

4. Discussion

Unlike previous efforts in creating multispectral or broadband SNSPDs, the dual-spectral SNSPD proposed in this work utilizes both multilayer-nanowire structures and multiple optical absorption resonances.

Early work into the development of multispectral or broadband SNSPDs has shown promising results in achieving high SDE across specific wavelength ranges, through strategies such as utilizing a single nanowire layer in conjunction with a special dielectric stack, which generates distinct reflected waves on the mirror surface that results in multiple absorption resonances [11,12]. Furthermore, employing multiple nanowire layers atop mirror structures has also been explored to enhance the overall SDE [13–15]. Contrary to previous studies, we proposed a special dual-band SNSPD design. Inserting nanowires in two regions of the SNSPD, we created a dual-spectral detector capable of distinguishing incident single photons based on whether they have a wavelength of about 1164 nm or within the 1440 to 2000 nm region. Regarding photon wavelength sensitivity, this special design has the potential to be utilized in quantum communication applications when different signals represented using varying wavelengths need to be distinguished from one another.

Here, we also demonstrate why multiple layers of nanowires are utilized. Due to the high reflectance of the gold mirror and strong electric field intensity in the first SiO_2 layer, the uppermost NbN has high absorption potential for some wavelengths > 1400 nm. To better achieve an ideal dual-spectral SNSPD with this design, multiple layers of NbN nanowires are employed to mitigate this unwanted effect. According to the simulation results, this approach proves to be effective as we observe a significant drop in absorptance of the nanowire positioned in Region 1 for longer wavelengths.

Nevertheless, this device still has two limitations. The first arises from the phase dispersion caused by the DBR, resulting in a significantly constrained bandwidth for wavelengths around 1164 nm. Second, due to absorption resonance introduced by the gold mirror in the first few layers of the DBR, the uppermost nanowire embedded within the first SiO_2 layer still absorbs some photons with longer wavelengths. The creation of two well-separated absorption bands is of course the ideal result. However, due to the gold mirror's high reflectance, some unwanted absorption resonances in the uppermost SiO_2 layer are unavoidable. This means the uppermost nanowire might absorb photons with wavelengths > 1400 nm as well. While this effect can be mitigated by stacking more layers of nanowires in Region 2, such a phenomenon still decreases the overall efficiency, while increasing the fabrication cost of the SNSPD. Future investigation of how to better control wave interference within a dielectric stack is required to create a multispectral SNSPD with high wavelength resolution. If the interference in the dielectric stack can be manipulated, multiple layers of nanowires and DBRs can replace the gold mirror, creating an ideal and efficient multispectral SNSPD.

Furthermore, it is worth emphasizing that the detection efficiency and the dual-band characteristic of the SNSPD will depend on the photon polarization due to the nanowire meander structure utilized in this paper. The proposed design works best when the nanowire is parallel to the incident photon polarization. If nanowires are patterned differently, such as into Peano curves [22], they thus decrease the polarization sensitivity and the performance dependent on polarization would be minimized.

In addition, while this work describes a SNSPD design sensitive to photons with wavelengths ranging from 1070 to 2000 nm, it is important to note that this device is tunable. By changing the target wavelength of the DBR and placing the nanowires at the position with the strongest absorption resonance, it is possible to change the target wavelength of the SNSPD. For example, using the structure depicted in Figure 7a, the simulated absorptance for Region 1 and Region 2 are shown in Figure 7b.

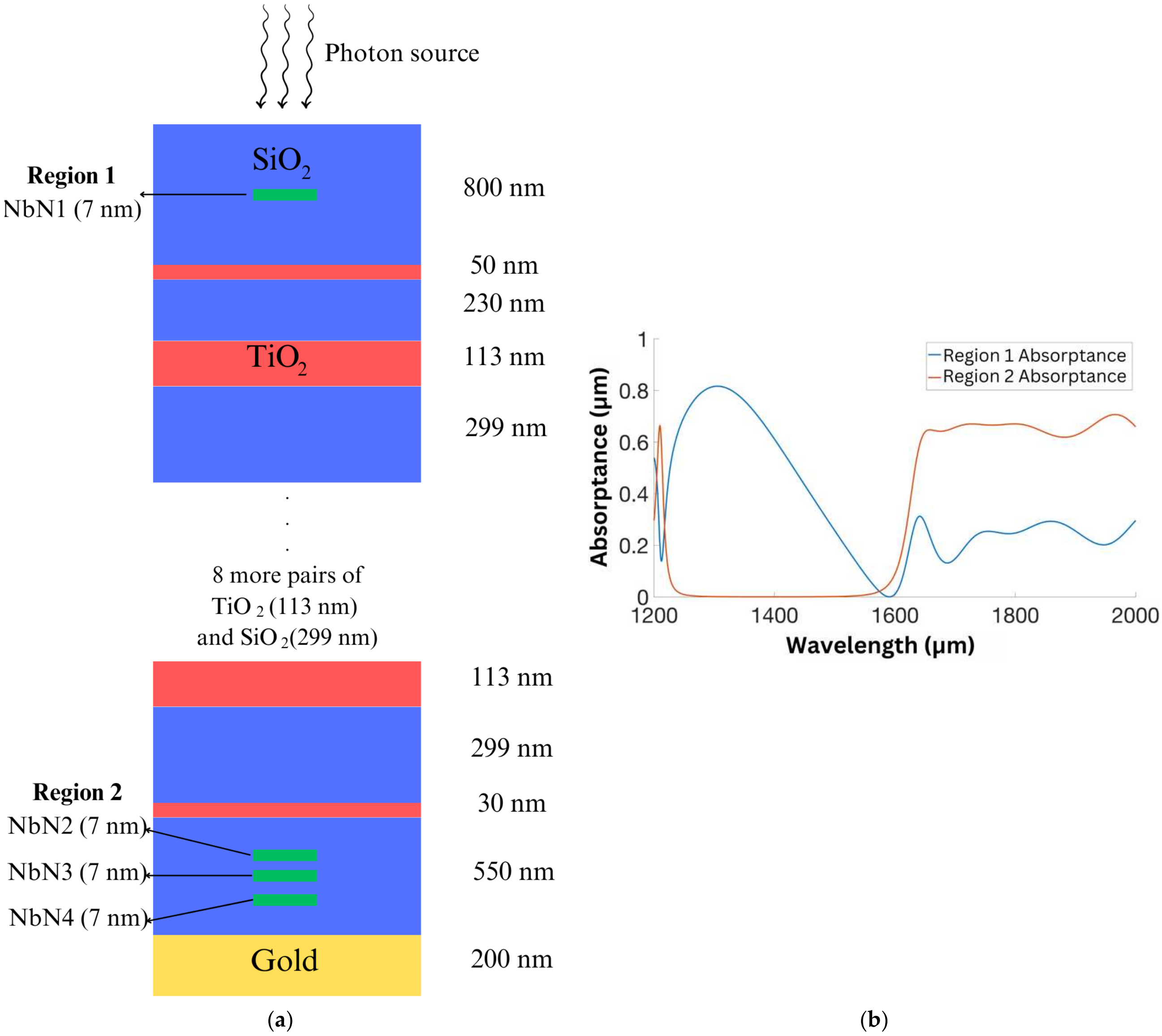

Figure 7. (**a**) Schematic of an alternative SNSPD design targeting different wavelengths. (**b**) The absorptance as a function of wavelength for Region 1 and Region 2 of the SNSPD.

As for our future experimental plans, we intend to use PVD techniques for the SNSPD thin film fabrication. In detail, for the gold layer TiO_2/SiO_2 DBR structure and the gold contacts E-beam evaporation will be utilized, while sputtering will be used for the NbN layers. We will employ E-beam Lithography and Reactive Ion Etching for the NbN nanowire meander structures. The characterization of the SNSPD will take place at the 4 Kelvin stage in a cryogenics system with attenuated pulsed laser, measuring the detection efficiency and dual-band characteristic, while performing a scan across the target light wavelength. Finally, we also expect to test the SNSPD device with FTIR for reflectance in room temperature for comparison.

Geometry errors and other systematic uncertainties introduced by the fabrication process would affect the device's dual-band characteristic and detection efficiency. However, given the results of our simulation, the errors in the positioning of the fabricated components will have a minimal impact on the overall performance and single-photon detection efficiency of the proposed SNSPD. The nanowire in Region 1 can be used as an example to illustrate this. Even if the position of NbN1 deviates by 50 nm from the simulation setup described above, the resulting difference in peak absorptance in the reflectance spectrum is expected to be less than 1%.

Finally, while the fabrication error on the DBR layer thickness would influence the filtering bandwidth, causing a shift on the dual-band absorptance spectrum, we plan to set the simulation parameters utilizing measurements performed on a gold-DBR mirror reflectance experiment using FTIR. There may also be degradation in fabrication due to the large total thickness or the switching between the DBR and NbN nanowire meander fabrication steps. The impact of this effect will be estimated through future experimental measurements.

5. Conclusions

In this work, we proposed a new dual-spectral SNSPD design, in which we stack a DBR on top of a gold mirror to achieve two distinct absorption bands. After tuning the thickness of the dielectrics and calculating the optimal positions for the nanowires, each nanowire positioned at those locations exhibits strong absorption resonance. By utilizing a modified DBR and a gold mirror as reflectors, the SNSPD design proposed in this work provides photon wavelength sensitivity in different tunable bands, opening up its potential applications for future quantum communication technology.

Author Contributions: Conceptualization, P.-H.W. and H.-Y.W.; simulation, P.-H.W.; analysis, P.-H.W., H.-Y.W. and S.P.; draft preparation, P.-H.W.; manuscript review and editing, P.-H.W., H.-Y.W. and S.P.; supervision, H.-Y.W. and S.P. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge the support by the Taiwan Instrumentation and Detector Consortium Programme of the funding agency NSTC (112L104013).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Li, W.; Zhang, L.; Tan, H.; Lu, Y.; Liao, S.-K.; Huang, J.; Li, H.; Wang, Z.; Mao, H.-K.; Yan, B.; et al. High-rate quantum key distribution exceeding 110 Mb s-1. *Nat. Photonics* **2023**, *17*, 416–421. [CrossRef]
2. Grünenfelder, F.; Boaron, A.; Resta, G.V.; Perrenoud, M.; Rusca, D.; Barreiro, C.; Houlmann, R.; Sax, R.; Stasi, L.; El-Khoury, S.; et al. Fast single-photon detectors and real-time key distillation enable high secret-key-rate quantum key distribution systems. *Nat. Photonics* **2023**, *17*, 422–426. [CrossRef]
3. Shi, Z.; Wang, W.; Wu, X.; Yang, L. A Technique for Measuring Dynamic Slot-Power of Optical PPM Signals Based on SNSPD. *IEEE Photonics Technol. Lett.* **2022**, *34*, 1377–1380. [CrossRef]
4. Guan, Y.; Li, H.; Xue, L.; Yin, R.; Zhang, L.; Wang, H.; Zhu, G.; Kang, L.; Chen, J.; Wu, P. Lidar with superconducting nanowire single-photon detectors: Recent advances and developments. *Opt. Lasers Eng.* **2022**, *156*, 107102. [CrossRef]
5. Zadeh, I.E.; Chang, J.; Los, J.W.N.; Gyger, S.; Elshaari, A.W.; Steinhauer, S.; Dorenbos, S.N.; Zwiller, V. Superconducting nanowire single-photon detectors: A perspective on evolution, state-of-the-art, future developments, and applications. *Appl. Phys. Lett.* **2021**, *118*, 190502. [CrossRef]
6. Gol'tsman, G.N.; Okunev, O.; Chulkova, G.; Lipatov, A.; Semenov, A.; Smirnov, K.; Voronov, B.; Dzardanov, A.; Williams, C.; Sobolewski, R. Picosecond superconducting single-photon optical detector. *Appl. Phys. Lett.* **2001**, *79*, 705–707. [CrossRef]
7. Chang, J.; Los, J.W.N.; Tenorio-Pearl, J.O.; Noordzij, N.; Gourgues, R.; Guardiani, A.; Zichi, J.R.; Pereira, S.F.; Urbach, H.P.; Zwiller, V. Detecting telecom single photons with (99.5 − 2.07 + 0.5)% system detection efficiency and high time resolution. *APL Photonics* **2021**, *6*, 036114. [CrossRef]
8. Marsili, F.; Verma, V.B.; Stern, J.A.; Harrington, S.; Lita, A.E.; Gerrits, T.; Vayshenker, I.; Baek, B.; Shaw, M.D.; Mirin, R.P.; et al. Detecting single infrared photons with 93% system efficiency. *Nat. Photonics* **2013**, *7*, 210–214. [CrossRef]
9. Reddy, D.V.; Nerem, R.R.; Nam, S.W.; Mirin, R.P.; Verma, V.B. Superconducting nanowire single-photon detectors with 98% system detection efficiency at 1550 nm. *Optica* **2020**, *7*, 1649–1653. [CrossRef]
10. Omair, Z.; Hooten, S.; Yablonovitch, E. Optimized Optics for Highly Efficient Photovoltaic Devices. In Proceedings of the 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), Calgary, AB, Canada, 15–21 June 2020; pp. 1813–1815. [CrossRef]
11. Li, H.; Wang, H.; You, L.; Hu, P.; Shen, W.; Zhang, W.; Yang, X.; Zhang, L.; Zhou, H.; Wang, Z.; et al. Multispectral superconducting nanowire single photon detector. *Opt. Express* **2019**, *27*, 4727–4733. [CrossRef]

12. Wang, H.; Hu, P.; Xiao, Y.; Zhang, X.; Zhou, H.; Zhang, W.; Li, H.; You, L.; Wang, Z. Multispectral Superconducting Nanowire Single-Photon Detector Based on Thickness-Modulated Optical Film Stack. *IEEE Photonics J.* **2022**, *14*, 6816304. [CrossRef]
13. Li, H.; Wang, Y.; You, L.; Wang, H.; Zhou, H.; Hu, P.; Zhang, W.; Liu, X.; Yang, X.; Zhang, L.; et al. Supercontinuum single-photon detector using multilayer superconducting nanowires. *Photonics Res.* **2019**, *7*, 1425–1431. [CrossRef]
14. Florya, I.N.; Korneeva, Y.P.; Mikhailov, M.Y.; Devizenko, A.Y.; Korneev, A.A.; Goltsman, G.N. Photon counting statistics of superconducting single-photon detectors made of a three-layer WSi film. *Low Temp. Phys.* **2018**, *44*, 221–225. [CrossRef]
15. Salim, A.J.; Eftekharian, A.; Majedi, A.H. High quantum efficiency and low dark count rate in multi-layer superconducting nanowire single-photon detectors. *J. Appl. Phys.* **2014**, *115*, 054514. [CrossRef]
16. Liu, D.; Miki, S.; Yamashita, T.; You, L.; Wang, Z.; Terai, H. Multimode fiber-coupled superconducting nanowire single-photon detector with 70% system efficiency at visible wavelength. *Opt. Express* **2014**, *22*, 21167–21174. [CrossRef]
17. Gemmell, N.R.; McCarthy, A.; Liu, B.; Tanner, M.G.; Dorenbos, S.D.; Zwiller, V.; Patterson, M.S.; Buller, G.S.; Wilson, B.C.; Hadfield, R.H. Singlet oxygen luminescence detection with a fiber-coupled superconducting nanowire single-photon detector. *Opt. Express* **2013**, *21*, 5005–5013. [CrossRef]
18. Li, H.; Chen, S.; You, L.; Meng, W.; Wu, Z.; Zhang, Z.; Tang, K.; Zhang, L.; Zhang, W.; Yang, X.; et al. Superconducting nanowire single photon detector at 532 nm and demonstration in satellite laser ranging. *Opt. Express* **2016**, *24*, 3535–3542. [CrossRef]
19. Xue, L.; Li, Z.; Zhang, L.; Zhai, D.; Li, Y.; Zhang, S.; Li, M.; Kang, L.; Chen, J.; Wu, P.; et al. Satellite laser ranging using superconducting nanowire single-photon detectors at 1064 nm wavelength. *Opt. Lett.* **2016**, *41*, 3848–3851. [CrossRef]
20. Miao, W.-C.; Hong, Y.-H.; Hsiao, F.-H.; Chen, J.-D.; Chiang, H.; Lin, C.-L.; Lin, C.-C.; Chen, S.-C.; Kuo, H.-C. Modified Distributed Bragg Reflectors for Color Stability in InGaN Red Micro-LEDs. *Nanomaterials* **2023**, *13*, 661. [CrossRef]
21. Lin, K.-C.; Lee, W.-K.; Wang, B.-K.; Lin, Y.-H.; Chen, H.-H.; Song, Y.-H.; Huang, Y.-H.; Shih, L.-W.; Wu, C.-C. Modified distributed Bragg reflector for protecting organic light-emitting diode displays against ultraviolet light. *Opt. Express* **2021**, *29*, 7654–7665. [CrossRef] [PubMed]
22. Chi, X.; Zou, K.; Gu, C.; Zichi, J.; Cheng, Y.; Hu, N.; Lan, X.; Chen, S.; Lin, Z.; Zwiller, V.; et al. Fractal superconducting nanowire single-photon detectors with reduced polarization sensitivity. *Opt. Lett.* **2018**, *43*, 5017–5020. [CrossRef] [PubMed]