



HAL
open science

High-order topological states using alignment of different bandgaps in 1D superlattices

Konstantinos Papatryfonos, Anne Rodriguez, Edson Cardozo De Oliveira,
Norberto Daniel Lanzillotti-Kimura

► **To cite this version:**

Konstantinos Papatryfonos, Anne Rodriguez, Edson Cardozo De Oliveira, Norberto Daniel Lanzillotti-Kimura. High-order topological states using alignment of different bandgaps in 1D superlattices. SPIE Photonics Europe 2024, Apr 2024, Strasbourg, France. hal-04534105

HAL Id: hal-04534105

<https://cnrs.hal.science/hal-04534105>

Submitted on 5 Apr 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

High-order topological states using alignment of different bandgaps in 1D superlattices

Konstantinos Papatryfonos^a, Anne Rodriguez^a, Edson Cardozo de Oliveira^a, and Norberto Daniel Lanzillotti-Kimura^a

^aUniversité Paris-Saclay, C.N.R.S., Centre de Nanosciences et de Nanotechnologies (C2N), 10 Boulevard Thomas Gobert, 91120 Palaiseau, France

ABSTRACT

Acoustic interface states have been evidenced in superlattices with frequencies at tens to hundreds of GHz. A recently demonstrated scheme to generate interface states in one-dimensional superlattices is based on the principle of band inversion, obtained by concatenating two periodic lattices with inverted spatial mode symmetries around the bandgap. Most of the realizations exploit a given bandgap for which there is one symmetry inversion. In this work, we present high-order topological nanophononic interface states in multilayered structures, achieved by concatenating two superlattices with different bandgap orders centered around the same frequency. In this case, inverted mode symmetries are not required to achieve the interface state, which is enabled by modifying the unit cells of the two superlattices. We showcase designs for versatile topological devices where interface states can be simultaneously created across a wide frequency range. The topological modes can be experimentally accessed in Brillouin or pump-probe experiments. The ability to explore higher bandgap order acoustic interface states in the GHz range is unique in nanophononic superlattices due to the linear dispersion relation of acoustic phonons. The demonstrated systems can thus be exploited to investigate schemes that are difficult or impossible to study in electronics or optics, due to their non-linear dispersion relations.

Keywords: Nanophononics, interface states, band inversion, 1D superlattices, one-dimensional Su-Schrieffer-Heeger model, high-order bandgaps

1. INTRODUCTION

The study of periodic lattices with two elements in their unit cell, as characterized by the Su-Schrieffer-Heeger (SSH) model within the tight-binding approximation, marks a pivotal advancement in the creation of materials exhibiting topological properties.^{1,2} This breakthrough has paved the way for the exploration of topological states across a diverse range of excitations, including but not limited to photons,³⁻⁵ phonons,⁶⁻⁸ and polaritons,⁹⁻¹¹ highlighting the versatility and breadth of applications in the field. In the specific context of multilayered periodic lattices, such as distributed Bragg reflectors (DBRs), when concatenating two DBRs with inverted spatial mode symmetries around a gap, the emergence of topological interface states at the edges of high-reflectivity bandgaps has been demonstrated, further enriching the landscape of topological phenomena.^{8,12-14} This presents intriguing possibilities, as DBR or distributed feedback (DFB) mirror-based cavities are widely used in photonics applications, enabling high-quality and reliable cavities in various configurations.¹⁵⁻²⁴ Consequently, this may offer a promising avenue to seamlessly integrate topological structures with these established photonic technologies.

In recent years, the field of nanophononics has rapidly advanced holding significant potential to contribute in various relevant technological realms for practical applications.²⁵⁻³¹ Unlike the phenomena observed in optics or electronics, the unique linear dispersion relation of acoustic phonons allows for the exploration of topological interface states across a broad frequency spectrum, from tens to hundreds of GHz, showcasing an exceptional agreement between theoretical predictions and experimental observations.^{8,32-35} In this work, we extend the exploration of topological nanophononic interface states by engineering GaAs/AlAs DBRs with the same spatial mode symmetries across different high-order bandgaps. By concatenating two superlattices without band

N.D. Lanzillotti-Kimura: E-mail: daniel.kimura@c2n.upsaclay.fr

inversion, but having respectively an odd and an even bandgap aligned around the same frequency, we show that a robust interface state can be formed. Specifically, the first superlattice exhibits its third bandgap around 28 GHz, while the second superlattice has its second bandgap at this frequency. Our study highlights that inverted mode symmetries around the same bandgap, or different bandgaps without inverting symmetries can work interchangeably and have the same effect in generating interface states.

Benefiting from the linear dispersion relation, such nanophononic resonators can be used to engineer topological interface states at high order bandgaps. We provide here a specific example and analysis involving such topological states. This investigation opens avenues for exploring new physical phenomena within the topological domain. We believe that the emergent platform will enable the experimental mapping of foundational textbook scenarios, and inspire more complex topological structures in the future.

2. INTERFACE STATES AT HIGH-ORDER BANDGAPS

In the realm of topological superlattices, the concept of band inversion plays a critical role in the manifestation of topologically protected states. Band inversion occurs when two modes at the edges of a bandgap, characterized by opposite symmetries, reverse their energy ordering at an interface. This pivotal transition can be induced by fine-tuning the relative thicknesses of the two constituent layers within the superlattice’s unit cell. The concatenation of two distinct superlattices, each designed with layers of differing thicknesses—thus presenting inverted band structures—facilitates the emergence of topologically protected interface states. Such states are inherently robust, owing to their topological nature, and are immune to perturbations that do not close the bandgap.^{13,14,34}

The Zak phase, θ^{Zak} , serving as the one-dimensional (1D) counterpart to the Berry phase, offers a powerful method to characterize the topological properties of multilayered acoustic devices.^{36,37} Fundamentally, the formation of an interface state between two DBRs with opposing reflection phase signs, exemplifies a basic manifestation of topology in acoustics.^{12,13} The sign of the reflection phase, positive or negative, depends on the DBR’s specific configuration. For any given n^{th} bandgap, the sign of the reflection phase ($sgn(\phi)$) is determined by the formula:

$$sgn(\phi) = (-1)^n (-1)^l \times \exp\left(i \sum_{m=0}^{n-1} \theta_m^{Zak}\right), \quad (1)$$

where l represents the count of completely filled bandgaps beneath the n^{th} bandgap. This relation indicates that an interface state at the n^{th} bandgap is contingent upon the condition that the cumulative Zak phase ($\sum_{m=0}^{n-1} \theta_m^{Zak}$) aligns with $0 + 2p\pi$ for one DBR and $\sum_{m=0}^{n-1} \theta_m^{Zak} = \pi + 2p\pi, p \in \mathbb{N}$ for the other, where p belongs to the set of natural numbers (\mathbb{N}). It is important to note that the presence of an interface state within a particular bandgap does not guarantee its occurrence across other bandgaps, given the potential variability in the sum of θ^{Zak} values across different bands.

3. RESULTS AND DISCUSSION

A first demonstration that superlattices of different bandgap orders centered around the same frequency can be used to generate interface states has been provided by Rodriguez et al.⁸ It is crucial to understand that the principle of generating interface states is not universally applicable across bandgaps of different orders. We provide a characteristic demonstration of this in Figure 1. As illustrated in Fig. 1, an interface state arises when the modes flanking the bandgaps of interest exhibit identical symmetries in both superlattices. In this case one superlattice has its second bandgap aligned with the third bandgap of the second one. However, this is not the case if both DBRs have the same bandgaps aligned, or different bandgaps that are both odd or both even. This observation leads to a general rule: interface states are formed between an even and an odd bandgap when both display the same symmetries. Conversely, when concatenating two bandgaps that are both odd or both even, the creation of an interface state necessitates inverted symmetries between the two. The rationale behind this distinction lies not solely in the cumulative Zak phase contributions but also significantly in the order of the bandgap itself. The variation in the bandgap order introduces a nuanced complexity in the phase differences

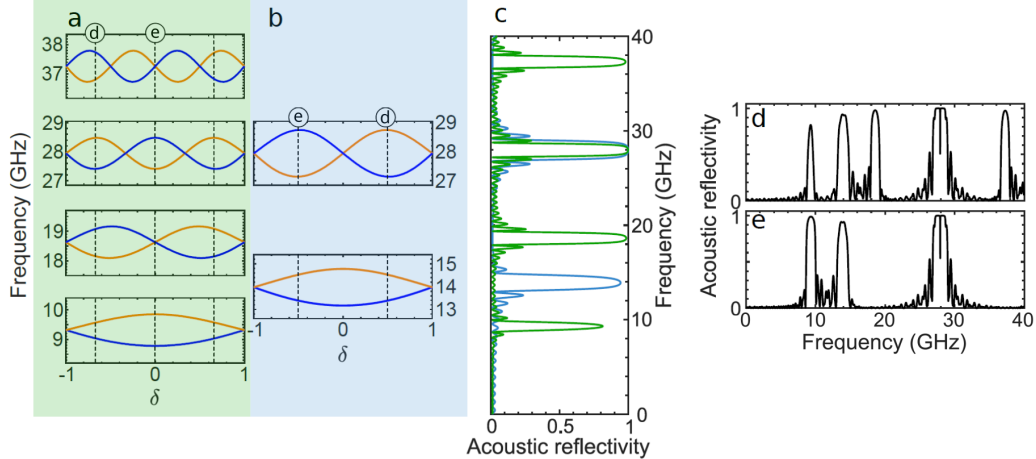


Figure 1. Illustration of the alignment of different acoustic bandgaps sharing the same frequency for two concatenated DBRs. (a, b) The third bandgap in superlattice a and the second bandgap in superlattice b exhibit identical central frequencies, demonstrating the alignment necessary for hybrid resonator formation. (c) Simulated acoustic reflectivity profiles for both DBRs, with the green and blue lines corresponding to panels a and b, respectively. (d, e) Simulated acoustic reflectivity spectra for two configurations of concatenated DBRs embedded within a GaAs matrix, with the ratio of the DBR unit cells, δ , indicated by the dashed lines in panels a and b.

of the reflection coefficient, underscoring the importance of both the Zak phase sum and the bandgap order in determining the possibility of interface state formation. This visualization highlights the reflective characteristics and frequency alignment of the two superlattices.

Topological interface states are renowned for their remarkable resilience against disorder, a feature that is critically advantageous for a variety of applications, notably in transport and flawless data communication.^{20,38,39} The principles described here, involving the generation of interface states either through band inversion or the combination of different bandgap orders around the same frequency, inherently maintain the central frequency of the bandgap despite potential variations in the unit cell ratio, δ . This robustness to any compositional inaccuracies, or even roughness, is integral to the construction of topological resonators. Such variations could naturally arise from factors like material intermixing or compositional inconsistencies during the epitaxial growth processes of superlattice layers.^{40,41} Our numerical analyses have confirmed that the interface mode’s robustness is consistently preserved across all studied bandgap orders, even when subjected to layer thickness ratio fluctuations, in agreement with Ref. 8.

In conclusion, through this study we have demonstrated a characteristic example elucidating the nuances involved in utilizing superlattices with differing bandgap orders around the same frequency. This investigation not only confirms the practical viability of utilizing this method for the development of topological resonators, but also accentuates the potential of superlattices as a refined tool for the exploration and exploitation of topological phenomena. Consequently, this opens up new pathways for innovative applications that leverage the unique properties of topological nanophononic interface states.

4. ACKNOWLEDGEMENT

The authors acknowledge funding from European Research Council Consolidator Grant No.101045089 (T-Recs). This work was supported by the European Commission in the form of the H2020 FET Proactive project No. 824140 (TOCHA).

REFERENCES

- [1] Su, W. P., Schrieffer, J. R., and Heeger, A. J., “Solitons in Polyacetylene,” *Physical Review Letters* **42**, 1698–1701 (June 1979).

- [2] Asbóth, J., Oroszlány, L., and Pályi, A., [*A Short Course on Topological Insulators*], no. 919 in Lecture Notes in Physics, Springer (2016).
- [3] Ozawa, T., Price, H. M., Amo, A., Goldman, N., Hafezi, M., Lu, L., Rechtsman, M. C., Schuster, D., Simon, J., Zilberberg, O., and Carusotto, I., “Topological photonics,” *Reviews of Modern Physics* **91**, 015006 (Mar. 2019).
- [4] Hauff, N. V., Le Jeannic, H., Lodahl, P., Hughes, S., and Rotenberg, N., “Chiral quantum optics in broken-symmetry and topological photonic crystal waveguides,” *Physical Review Research* **4**, 023082 (Apr. 2022).
- [5] Khanikaev, A. B. and Shvets, G., “Two-dimensional topological photonics,” *Nature Photonics* **11**, 763–773 (Dec. 2017).
- [6] Esmann, M., Lamberti, F. R., Lemaître, A., and Lanzillotti-Kimura, N. D., “Topological acoustics in coupled nanocavity arrays,” *Physical Review B* **98**, 161109 (Oct. 2018).
- [7] Arregui, G., Ortíz, O., Esmann, M., Sotomayor-Torres, C. M., Gomez-Carbonell, C., Mauguin, O., Perrin, B., Lemaître, A., García, P. D., and Lanzillotti-Kimura, N. D., “Coherent generation and detection of acoustic phonons in topological nanocavities,” *APL Photonics* **4**, 030805 (Mar. 2019).
- [8] Rodriguez, A., Papatryfonos, K., Cardozo De Oliveira, E. R., and Lanzillotti-Kimura, N. D., “Topological nanophononic interface states using high-order bandgaps in the one-dimensional Su-Schrieffer-Heeger model,” *Physical Review B* **108**, 205301 (Nov. 2023).
- [9] St-Jean, P., Dauphin, A., Massignan, P., Real, B., Jamadi, O., Milicevic, M., Lemaître, A., Harouri, A., Le Gratiet, L., Sagnes, I., Ravets, S., Bloch, J., and Amo, A., “Measuring Topological Invariants in a Polaritonic Analog of Graphene,” *Physical Review Letters* **126**, 127403 (Mar. 2021).
- [10] Pernet, N., St-Jean, P., Solnyshkov, D. D., Malpuech, G., Carlon Zambon, N., Fontaine, Q., Real, B., Jamadi, O., Lemaître, A., Morassi, M., Le Gratiet, L., Baptiste, T., Harouri, A., Sagnes, I., Amo, A., Ravets, S., and Bloch, J., “Gap solitons in a one-dimensional driven-dissipative topological lattice,” *Nature Physics* **18**, 678–684 (June 2022).
- [11] Klemmt, S., Harder, T. H., Egorov, O. A., Winkler, K., Ge, R., Bandres, M. A., Emmerling, M., Worschech, L., Liew, T. C. H., Segev, M., Schneider, C., and Höfling, S., “Exciton-polariton topological insulator,” *Nature* **562**, 552–556 (Oct. 2018).
- [12] Xiao, M., Zhang, Z., and Chan, C., “Surface Impedance and Bulk Band Geometric Phases in One-Dimensional Systems,” *Physical Review X* **4**, 021017 (Apr. 2014).
- [13] Esmann, M., Lamberti, F. R., Senellart, P., Favero, I., Krebs, O., Lanco, L., Gomez Carbonell, C., Lemaître, A., and Lanzillotti-Kimura, N. D., “Topological nanophononic states by band inversion,” *Physical Review B* **97**, 155422 (Apr. 2018).
- [14] Esmann, M. and Lanzillotti-Kimura, N. D., “A Topological View on Optical and Phononic Fabry–Perot Microcavities through the Su–Schrieffer–Heeger Model,” *Applied Sciences* **8**, 527 (Apr. 2018).
- [15] Somaschi, N., Giesz, V., De Santis, L., Loredò, J. C., Almeida, M. P., Hornecker, G., Portalupi, S. L., Grange, T., Antón, C., Demory, J., Gómez, C., Sagnes, I., Lanzillotti-Kimura, N. D., Lemaître, A., Auffeves, A., White, A. G., Lanco, L., and Senellart, P., “Near-optimal single-photon sources in the solid state,” *Nature Photonics* **10**, 340–345 (May 2016).
- [16] Amo, A., Pigeon, S., Sanvitto, D., Sala, V. G., Hivet, R., Carusotto, I., Pisanello, F., Leménager, G., Houdré, R., Giacobino, E., Ciuti, C., and Bramati, A., “Polariton Superfluids Reveal Quantum Hydrodynamic Solitons,” *Science* **332**, 1167–1170 (June 2011).
- [17] Schneider, D., Liaqat, F., El Boudouti, E. H., El Hassouani, Y., Djafari-Rouhani, B., Tremel, W., Butt, H.-J., and Fytas, G., “Engineering the Hypersonic Phononic Band Gap of Hybrid Bragg Stacks,” *Nano Letters* **12**, 3101–3108 (June 2012).
- [18] Papatryfonos, K., Saladukha, D., Merghem, K., Joshi, S., Lelarge, F., Bouchoule, S., Kazazis, D., Guilet, S., Le Gratiet, L., Ochalski, T. J., Huyet, G., Martinez, A., and Ramdane, A., “Laterally coupled distributed feedback lasers emitting at 2 μm with quantum dash active region and high-duty-cycle etched semiconductor gratings,” *Journal of Applied Physics* **121** (02 2017).
- [19] Papatryfonos, K., Joshi, S., Merghem, K., Bouchoule, S., Guilet, S., Le Gratiet, L., Martinez, A., and Ramdane, A., “Quantum dash based lasers for gas sensing,” in [*26th International Conference on Indium Phosphide and Related Materials (IPRM)*], 1–2, IEEE, Montpellier (May 2014).

- [20] Papatryfonos, K., Selviah, D. R., Maman, A., Hasharoni, K., Brimont, A., Zanzi, A., Kraft, J., Sidorov, V., Seifried, M., Baumgartner, Y., Horst, F., Offrein, B. J., Lawniczuk, K., Broeke, R. G., Terzenidis, N., Mourgias-Alexandris, G., Tang, M., Seeds, A. J., Liu, H., Sanchis, P., Moralis-Pegios, M., Manolis, T., Pleros, N., Vyrsoinos, K., Sirbu, B., Eichhammer, Y., Oppermann, H., and Tekin, T., “Co-Package Technology Platform for Low-Power and Low-Cost Data Centers,” *Applied Sciences* **11**, 6098 (June 2021).
- [21] Wang, J., Bai, Y., Liu, H., Cheng, Z., Tang, M., Chen, S., Wu, J., Papatryfonos, K., Liu, Z., Huang, Y., and Ren, X., “Optimization of 1.3 μm InAs/GaAs quantum dot lasers epitaxially grown on silicon: taking the optical loss of metamorphic epilayers into account,” *Laser Physics* **28**, 126206 (Oct 2018).
- [22] Orieux, A., Versteegh, M. A. M., Jöns, K. D., and Ducci, S., “Semiconductor devices for entangled photon pair generation: a review,” *Reports on Progress in Physics* **80**, 076001 (May 2017).
- [23] Engel, L., Kolatschek, S., Herzog, T., Vollmer, S., Jetter, M., Portalupi, S. L., and Michler, P., “Purcell enhanced single-photon emission from a quantum dot coupled to a truncated Gaussian microcavity,” *Applied Physics Letters* **122**, 043503 (Jan. 2023).
- [24] Dusanowski, L., Nawrath, C., Portalupi, S. L., Jetter, M., Huber, T., Klemmt, S., Michler, P., and Höfling, S., “Optical charge injection and coherent control of a quantum-dot spin-qubit emitting at telecom wavelengths,” *Nature Communications* **13**, 748 (Feb. 2022).
- [25] Priya, Cardozo de Oliveira, E. R., and Lanzillotti-Kimura, N. D., “Perspectives on high-frequency nanomechanics, nanoacoustics, and nanophononics,” *Applied Physics Letters* **122**, 140501 (Apr. 2023).
- [26] Ortiz, O., Pastier, F., Rodriguez, A., Priya, Lemaitre, A., Gomez-Carbonell, C., Sagnes, I., Harouri, A., Senellart, P., Giesz, V., Esmann, M., and Lanzillotti-Kimura, N. D., “Fiber-integrated microcavities for efficient generation of coherent acoustic phonons,” *Applied Physics Letters* **117**, 183102 (Nov. 2020).
- [27] Lanzillotti-Kimura, N. D., Fainstein, A., Lemaitre, A., and Jusserand, B., “Nanowave devices for terahertz acoustic phonons,” *Applied Physics Letters* **88**, 083113 (Feb. 2006).
- [28] Lanzillotti-Kimura, N. D., Fainstein, A., Jusserand, B., Lemaitre, A., Mauguin, O., and Largeau, L., “Acoustic phonon nanowave devices based on aperiodic multilayers: Experiments and theory,” *Physical Review B* **76**, 174301 (Nov. 2007).
- [29] Vasileiadis, T., Reparaz, J. S., and Graczykowski, B., “Phonon transport in the gigahertz to terahertz range: Confinement, topology, and second sound,” *Journal of Applied Physics* **131**, 180901 (May 2022).
- [30] Volz, S., Ordonez-Miranda, J., Shchepetov, A., Prunnila, M., Ahopelto, J., Pezeril, T., Vaudel, G., Gusev, V., Ruello, P., Weig, E. M., Schubert, M., Hettich, M., Grossman, M., Dekorsy, T., Alzina, F., Graczykowski, B., Chavez-Angel, E., Sebastian Reparaz, J., Wagner, M. R., Sotomayor-Torres, C. M., Xiong, S., Neogi, S., and Donadio, D., “Nanophononics: state of the art and perspectives,” *The European Physical Journal B* **89**, 15 (Jan. 2016).
- [31] Ng, R. C., El Sachat, A., Cespedes, F., Poblet, M., Madiot, G., Jaramillo-Fernandez, J., Florez, O., Xiao, P., Sledzinska, M., Sotomayor-Torres, C. M., and Chavez-Angel, E., “Excitation and detection of acoustic phonons in nanoscale systems,” *Nanoscale* **14**(37), 13428–13451 (2022).
- [32] Parappurath, N., Alpeggiani, F., Kuipers, L., and Verhagen, E., “Direct observation of topological edge states in silicon photonic crystals: Spin, dispersion, and chiral routing,” *Science Advances* **6**, eaaw4137 (Mar. 2020).
- [33] Delsing, P., Cleland, A. N., Schuetz, M. J. A., Knörzer, J., Giedke, G., Cirac, J. I., Srinivasan, K., Wu, M., Balram, K. C., Bäuerle, C., Meunier, T., Ford, C. J. B., Santos, P. V., Cerda-Méndez, E., Wang, H., Krenner, H. J., Nysten, E. D. S., Weiß, M., Nash, G. R., Thevenard, L., Gourdon, C., Rovillain, P., Marangolo, M., Duquesne, J.-Y., Fischerauer, G., Ruile, W., Reiner, A., Paschke, B., Denysenko, D., Volkmer, D., Wixforth, A., Bruus, H., Wiklund, M., Reboud, J., Cooper, J. M., Fu, Y., Brugger, M. S., Rehfeldt, F., and Westerhausen, C., “The 2019 surface acoustic waves roadmap,” *Journal of Physics D: Applied Physics* **52**, 353001 (July 2019).
- [34] Ortiz, O., Priya, P., Rodriguez, A., Lemaitre, A., Esmann, M., and Lanzillotti-Kimura, N. D., “Topological optical and phononic interface mode by simultaneous band inversion,” *Optica* **8**, 598 (May 2021).
- [35] Esmann, M., Lamberti, F. R., Harouri, A., Lanco, L., Sagnes, I., Favero, I., Aubin, G., Gomez-Carbonell, C., Lemaitre, A., Krebs, O., Senellart, P., and Lanzillotti-Kimura, N. D., “Brillouin scattering in hybrid optophononic Bragg micropillar resonators at 300 GHz,” *Optica* **6**, 854 (July 2019).

- [36] Berry, M. V., “Quantal phase factors accompanying adiabatic changes,” *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences* **392**(1802), 45–57 (1984).
- [37] Zak, J., “Berry’s phase for energy bands in solids,” *Physical Review Letters* **62**, 2747–2750 (June 1989).
- [38] Mathew, J. P., Pino, J. d., and Verhagen, E., “Synthetic gauge fields for phonon transport in a nano-optomechanical system,” *Nature Nanotechnology* **15**, 198–202 (Mar. 2020).
- [39] Arora, S., Bauer, T., Barczyk, R., Verhagen, E., and Kuipers, L., “Direct quantification of topological protection in symmetry-protected photonic edge states at telecom wavelengths,” *Light: Science & Applications* **10**, 9 (Jan. 2021).
- [40] Papatryfonos, K., Angelova, T., Brimont, A., Reid, B., Guldin, S., Smith, P. R., Tang, M., Li, K., Seeds, A. J., Liu, H., and Selviah, D. R., “Refractive indices of mbe-grown $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ternary alloys in the transparent wavelength region,” *AIP Advances* **11**(2), 025327 (2021).
- [41] Papatryfonos, K., Rodary, G., David, C., Lelarge, F., Ramdane, A., and Girard, J.-C., “One-dimensional nature of InAs/InP quantum dashes revealed by scanning tunneling spectroscopy,” *Nano Letters* **15**(7), 4488–4497 (2015). PMID: 26076402.