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# THE ROLE OF OPTICAL SOLITONS IN OPTICAL COMMUNICATIONS

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**Abstract-**Modern optical communication systems demand high-speed data transmission with minimal signal distortion over long distances. One of the most effective solutions to mitigate the effects of dispersion and nonlinearity in optical fibers is the use of optical solitons—nonlinear light pulses that can maintain their shape during propagation. This study explores the role and dynamics of solitons in various optical fiber configurations, including conventional fibers, Fiber Bragg Gratings (FBG), and gas-filled hollow-core fibers. Through numerical simulations using the Split-Step Fourier Method (SSFM) and Step-Split Method, it is shown that a balance between Group Velocity Dispersion (GVD) and Self-Phase Modulation (SPM) allows for the formation of stable soliton pulses. Previous research highlights the influence of fiber loss, higher-order dispersion, and structural parameters on pulse stability and symmetry. Furthermore, recent advancements in gas-filled hollow-core fibers have enabled broader spectral coverage and higher propagation intensities, leading to extreme pulse compression on the sub-femtosecond scale and tunable dispersive wave emission. This review affirms that optical solitons are not only of theoretical significance but also hold great promise for practical applications in high-speed optical communication and ultrafast light generation technologies.

**Keywords:** *Optical soliton, fiber optics, nonlinear propagation*

## 1 Introduction

Education serves as a tool to produce high-quality human resources, Slameto stated that education is an important component in life. To achieve the level of educational success, it is necessary to create a learning environment that supports a student. This must provide support for the teaching and learning process and provide a conducive environment for a learner.(Gare, Lolowang and Polii, 2022).

Physics lessons help students analyze something. In addition, physics education teaches students about the universe, helps them think and reason, improves their reasoning ability, and enhances their thinking power. Physics learning should be evaluated because of its importance in the process of analyzing something.(Cahyono, 2023). Learning is a system that relates to elements of analyzing materials, evaluation, and learning methods. Therefore, learning modules can be used to guide the learning process. Learning methods in implementing good physical education and supported by a creative and innovative student in understanding physics education can be used in this learning approach to analyze problems. The motivation given by a student is very useful in the learning process, which will be very much in demand by many people.(Prakoso, Wahyudi and Masykuroh, 2021).

The development of optical communication technology is one of the main pillars in supporting the need for large-capacity, high-speed data transmission with minimal interference. Fiber-optic communication systems have proven to be superior to conventional systems because they have advantages such as large bandwidth capacity, low attenuation levels, and resistance to electromagnetic interference.

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However, in its application, optical signal transmission still faces major challenges such as dispersion and nonlinearity effects that can cause pulse broadening and information distortion during the propagation process. One interesting solution to overcome these problems is to utilize optical solitons—a form of nonlinear light pulse that is able to maintain its shape stably throughout the propagation path.

Optical solitons were first developed theoretically by Hasegawa and Tappert, which was then proven experimentally by Mollenauer. This phenomenon arises due to the balance between the Group Velocity Dispersion (GVD) effect which tends to widen the pulse, and the Kerr nonlinearity effect which causes phase changes that compress the pulse. In a study conducted by(Zen, Hidayat and Shiddiq, 2002)Zen et al. (2002), simulated the propagation of solitons in optical fibers by considering factors such as fiber loss, high-order dispersion ($\beta_3$), and nonlinearity. This study uses the Split-Step Fourier Method as a numerical approach to solve the Nonlinear Schrödinger Equation (NLS) and proves that soliton pulses can be formed stably when the dispersion scale length (LD) approaches the nonlinear scale length (LNL). Furthermore, the simulation results show that the addition of fiber loss reduces the pulse intensity, while the presence of high-order dispersion affects the symmetry of the pulse shape.

In the development of fiber optic technology, not only the characteristics of the material are considered, but also the fiber structure such as Fiber Bragg Grating (FBG) which allows the reflection of certain wavelengths of light and is very useful in controlling dispersion. The study conducted by(Siahaan, 2015)Siahaan et al. (2015) studied the formation of soliton waves in FBGs using the Step-Split numerical method approach using MATLAB software. This study shows that with variations in the parameters α, β, and γ, as well as the use of the Kerr nonlinear effect, solitons can still form stably in FBGs.(Zulfitri, 2022). The simulations also show that the right configuration of parameter values will produce deeper wave well potential, high amplitude, and pulse stability even in a medium with high reflectivity. This proves that solitons can exist not only in conventional optical fibers, but also in complex optical structures such as FBGs, making it a flexible and adaptive technology in modern transmission systems.(Sukmayadi, 2014).

Furthermore, the utilization of solitons in modern optical communication systems such as Dense Wavelength Division Multiplexing (DWDM) has also been studied by(Prakoso, Wahyudi and Masykuroh, 2021)Prakoso et al. (2021). In this study, the focus is directed at optimizing the Bit Error Rate (BER) in a soliton-based DWDM system with a hybrid optical amplifier configuration, namely a combination of Erbium Doped Fiber Amplifier (EDFA) and Raman Optical Amplifier (ROA).(Ummah, 2019). The simulation results show that the amplifier placement scenario in the Inline-Preamplifier position is able to provide the best BER performance of up to $8.97\times10^{-23}$, compared to other scenarios. In addition, this study also proves that even though the length of the optical fiber increases, a soliton-based system with proper amplifier can still maintain decent transmission performance up to 60 km. This shows that the use of solitons is not only important in the context of pulse stability, but also in improving signal quality and energy efficiency in long-distance optical transmission systems.

Overall, various studies that have been conducted show that optical solitons have a strategic role in the revolution of modern optical communications. Not only as a solution for dispersion compensation and signal stabilizer, but also as a technology that can be integrated into various transmission system architectures, both on conventional and complex scales such as FBG and DWDM. With the support of accurate numerical approaches such as the Split-Step Fourier Method and Step-Split Method, the design of soliton-based communication systems can continue to be developed to meet the demands of the increasingly fast and data-intensive digital era.(Gangwar, Singh and Singh, 2007).

## 2 Research methods

The type of research used is descriptive. Descriptive research is research that provides a description of a situation, problem, phenomenon, service, or plan, or provides information about the conditions and conditions of community life, attitudes, opinions, and life processes, as well as careful measurement of social phenomena.(Sukmayadi, 2014). Researchers usually conceptualize and collect data, but they do not test hypotheses. Data collected for descriptive research consists of text, words, symbols, and images. Therefore, to explain the delivery of the report, the research report will contain data excerpts.(Li et al., 2024).

The researcher used a descriptive qualitative research methodology. The researcher used a literature research method to collect and analyze data from various published journals.(Kivshar, Agrawal and Agrawal, 2003). To collect data, researchers use the library study data collection method to collect relevant or relevant data for research from scientific articles, news, and other reliable sources. The collected data are analyzed in a qualitative descriptive manner. To produce good results, researchers collect data from journals and other sources that are reliable and factual.(Mukhlis, Lesmono and Nuraini, 2021). By using experimental methods to analyze the role of optical solitons into a nonlinear pulse shape that is able to maintain its shape stably throughout the propagation path. And the addition of fiber loss to reduce the pulse intensity, while the presence of high-order dispersion affects the symmetry of the pulse shape(Kieu, 2011).

This study uses the Split-Step Fourier Method as a numerical approach to solve the Nonlinear Schrödinger Equation (NLS) and proves that soliton pulses can be formed stably when the dispersion scale length (LD) approaches the nonlinear scale length (LNL). Furthermore, the simulation results show that the addition of fiber loss reduces the pulse intensity, while the presence of high-order dispersion affects the symmetry of the pulse shape.(Saputra, Ripai and Abdullah, 2022).

## 3 Results and Discussion

Light pulses in optical fibers carry the vast majority of all telecommunications today. Compared to electrical pulses in cables, fiber-optic transmission is far superior, largely because of two fundamental advantages: light in fiber experiences very low power loss, and fiber provides very wide bandwidth.('Soliton_Research_Methods (1)', no date). For losses, a rough figure is 0.2 dB/km. This implies that even after 100 km, there is still 1% of the launch power remaining, which is unmatched. The available bandwidth can be estimated as 30 THz (perhaps 50 THz if one accepts slightly higher losses), which is several orders of magnitude better than anything achievable with electronics.(In and Fibers, 2015).

Further comparison of optical and electrical transmission brings us to the imperfections that both types of channels have, the group velocity is frequency dependent; Since any signal requires a certain bandwidth, the transmitted signal suffers from distortion due to group velocity dispersion.(Green, 2010). This is a linear distortion, which means it can be perfectly compensated for by adding an opposing dispersion element. However, in one respect, optical fiber is very different from electrical cables.(Hasegawa, 2022).

The response of glass to light is nonlinear, whereas copper to current is not (within reasonable limits). Therefore, the physics of transmitting data with light pulses through optical fiber is fundamentally different because it involves the nonlinear response of the material to the signal. Nonlinear distortion is not as easily compensated for as linear distortion.(Retna Apsari, Noriah Bidin, 2008). This has led to the widely held conception that the optical power in the fiber must always be kept low enough so that nonlinear distortion is avoided. To this argument, one can make two responses: One, nonlinearity can actually be put to good use, even used to advantage, when the soliton concept is adopted. This has been demonstrated even in commercial settings. Two, the ever-increasing demand for data carrying capacity(Mitschke, Mahnke and Hause, 2017).

The increasing need for future communications, which have large data capacities and high transmission speeds, is spurring the growth of various research into improving the performance of telecommunications systems.(Pebrianti and Kunci, 2006). The prospect was further improved when Hasegawa and Tappert theoretically demonstrated the possibility of utilizing solitons in fiber optic data transmission. Chromatic dispersion is a major problem in high bit rate transmission.(Green, 2010). To overcome this problem, dispersion compensation is performed. Dispersion balancing with Kerr nonlinearity is one of the dispersion compensation techniques. The result is a soliton pulse(Saputra, Ripai and Abdullah, 2022). The propagation of solitons in the system with the addition of EDFA devices is explained theoretically by the theory of guiding center (average) solitons.

This theory applies to bit rates where the amplifier spacing is shorter than the soliton period, and on the scale of amplifier spacing. During pulse propagation in optical fiber, power loss occurs.(Prabowo KA and Ambarini, 2022). Several factors that cause loss are absorption, Rayleigh scattering, bending losses, boundary losses, and splice loss1)(Cundiff et al., 1999). Light absorption occurs due to atomic defects in the composition of optical fibers, atomic impurities (extrinsic absorption) for example OH ions, basic materials that can also absorb light (intrinsic absorption).

In total, the loss calculation also includes losses caused by Rayleigh scattering, bent fiber profiles (bending losses), due to light scattering at the core-cladding boundary (boundary losses), and losses caused by optical fiber connections (splice losses).(Ereño and Benavides, 2022). The parameter used to express the loss or impermanence of physical quantities in fiber is called fiber loss. Mathematically, fiber loss (α) is related to the input power (P0), the length of the optical fiber (L), and the power that has been transmitted, exp( ) PT = P0 −αL . Technically, the unit used for fiber loss is dB/km(Yasin, 2016). The fiber loss value becomes minimum when using carrier wave at wavelength λ=1.55 μm, which is represented by the fiber loss measurement result. The use of EDFA as an amplifier in optical communication system can help overcome fiber loss.

When the fiber length L<<LD and L<<LNL, the dispersive effect and nonlinear effect do not give significant influence, so the right side of the equation can be ignored and this means that the wave has a solution U(Z,τ)=U(0,τ) meaning the pulse is stable. In this condition if the fiber loss is taken into account then the pulse experiences intensity reduction. That is why an amplifier is needed so that the pulse continues to propagate with the same amplitude as the initial amplitude. When the pulse propagates in a fiber system where L<<LNL but GVD is dominant (L ≥ LD), mathematically the right side of the equation ignores the last term and as a result the pulse evolution is dominated by the influence of GVD. Such a system will cause the pulse to drastically experience attenuation and pulse broadening (due to GVD) and asymmetry of its profile (due to β3).

The propagation equation for a light pulse in a fiber must contain these two effects, at least in leading order. An equation that fits this description is known as the nonlinear Schrödinger equation (NLSE).(Retna Apsari, Noriah Bidin, 2008). It plays a very central role in all nonlinear optical fibers.(Saleh, Hany and Aly, 2010). It describes the evolution of the pulse amplitude (fast oscillations at some central optical frequencies are omitted) in a reference frame moving along with the traveling light, that is, with the group velocity at.$\omega_0$ $\omega_0$(Sahelay, Ahirwal and Jain, 2012). Written in physical quantities, given by:

$$\frac{\partial}{i\partial z}A - \frac{\beta_2}{2}\frac{\partial^\alpha}{\partial t^2}A + \gamma|A|^2A = 0 \tag{1}$$

Here, A = A(z, t) is the complex amplitude with z the position along the fiber and t the retarded time. β2 is the group velocity dispersion coefficient, and γ is the nonlinearity coefficient.(Shahadatul Aini Binti Zainudin, 2012). Depending on the situation, it may be necessary to add corrective terms for losses, high-order dispersion or other nonlinear effects.(Hasanah, 2009). This equation gets its name from its formal similarity to the Schrödinger equation of quantum mechanical fame: The quantum mechanical version usually describes how a wave function spreads out in space as time passes; here, the equation describes how a short pulse broadens temporally as it propagates down a fiber.(Branch, 2011). Therefore, the space and time coordinates switch roles. The potential, in the nonlinear case, originates from the self-phase modulation, which is captured in terms of nonlinearity.(Green, 2010).

In the anomalous dispersion regime, NLSE Equation (1) supports stable solutions known as fundamental solitons:

$$(z,t) = \sqrt{P_0}\,\mathrm{sech}\left(\frac{(t-t_s) - \Omega\beta_2(z-z_s)}{T_0}\right) \tag{2}$$

$$\times \exp[i\frac{\gamma R}{2}(z-z_s) - i\Omega(t-t_s) - \frac{1}{2}\Omega\beta_2)(z-2\varsigma) + i\varphi_s] \tag{3}$$

Here, is the peak power; is the pulse duration; Ω is the deviation of the soliton center optical frequency from the reference frame,. TS, Zs and Φs are the initial values of the center time, initial position and phase offset, respectively.$p_0 T_0\ w_0$(Hasegawa, 2022). As long as a single soliton is considered, the frequency offset and initial value can be set to zero without loss of generality so that a very simplified version(Green, 2010):

$$(z, t] = \sqrt{p_0}\,\text{sech}\left(\frac{1}{T_0}\right) lx\,p\left[\frac{1^{yp_0}}{2} z\right] \tag{4}$$

This shows that in a dispersive medium, nonzero frequencies translate into relative motion, so frequencies are usually referred to as velocities. The number of solitons is also conserved, even in cases when there is more than one(Prakoso, Wahyudi and Masykuroh, 2021).

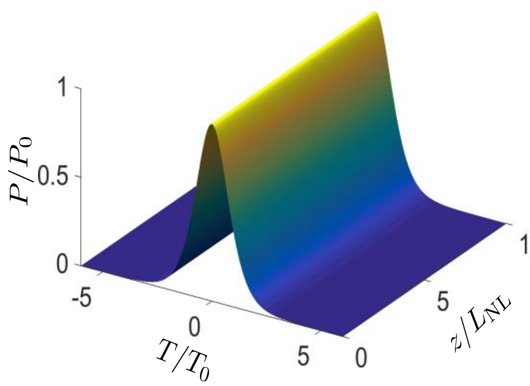


Figure 1. Evolution of solitons of the basic nonlinear Schrödinger equation (NLSE) Radiation and Higher-Order Solitons

The nonlinear Schroedinger equation can be derived from Maxwell's equations 1)(Pebrianti and Kunci, 2006). By taking into account loss (α), high-order dispersion (β3), and high-order nonlinear terms, we obtain:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \frac{i}{2}\beta_2 \frac{2^2 A}{\partial T^2} - \frac{1}{6}\beta_3 \frac{j^3 A}{\partial T^3} \tag{5}$$

$T=t-Z$is the retarded time, namely the time Vg is measured in a reference frame moving with group velocity Vg = 1/β1, Z is the propagation distance, α is the fiber loss, γ is the nonlinear coefficient defined n2ω0 , TR is related to the Raman gai(Branch, 2011). The nature of wave propagation based on the influence of GVD and SPM, can be grouped into 4 categories based on the relative value of the length scale L (fiber length), LD (dispersion length), LNL (nonlinear length). The LD scale shows the emergence of a significant dispersion effect after the wave passes a distance of LD, as well as the nonlinear effect on the wave will be dominant after the wave travels as far as LNL. Mathematically, LD and LNL have a dependence on the initial pulse value, T0 (pulse width) and P0 (maximum power/peak power).

## 4 Conclusion

Optical solitons have been proven to be an effective solution to overcome major challenges in optical communication systems, especially in compensating for the effects of dispersion and nonlinearity during signal propagation in optical fibers. Based on the results of numerical studies using the Split-Step Fourier and Step-Split methods, soliton waves are able to maintain their shape and stability in various media configurations, such as conventional optical fibers and Fiber Bragg Grating (FBG). The balance between Group Velocity Dispersion (GVD) and Self-Phase Modulation (SPM) is the main key in the formation of stable solitons. In addition, recent studies have shown that the development of gas-filled hollow fibers opens up new opportunities in producing high-energy solitons, extreme pulse compression to sub-femtosecond scales, and precisely tunable dispersive wave emissions. These advantages make optical solitons not only relevant in a theoretical context, but also very potential in practical applications, especially for high-speed optical communication systems, multi-channel systems, and ultrafast laser technology. With the flexibility of physical parameter settings and their adaptability to various fiber structures, optical solitons will continue to be a key element in the development of next-generation optical technologies.

## Reference

Branch, M. (2011) 'dbkbo^qflk=lc=nr^kqrj=`labp=rpfkd=rm=^ka=altk== ifkh=lmqf`^i=plifqlk=', 55(1), pp. 97–106.

Cahyono, A.E. (2023) 'Membangun Kemandirian Belajar Untuk Mengatasi Learning Loss Dalam Pembelajaran Berdiferensiasi', *Education Journal : Journal Educational Research and Development*, 7(2), pp. 167–174. Available at: https://doi.org/10.31537/ej.v7i2.1257.

Cundiff, S.T. *et al.* (1999) 'Observation of polarization-locked vector solitons in an optical fiber', *Physical Review Letters*, 82(20), pp. 3988–3991. Available at: https://doi.org/10.1103/PhysRevLett.82.3988.

Ereño, R.E. and Benavides, N.G. (2022) 'Reflections on the Least Learned Competencies in Mathematics', *UIJRT | United International Journal for Research & Technology |*, 03(08), p. 8.

Gangwar, R., Singh, S.P. and Singh, N. (2007) 'SOLITON BASED OPTICAL COMMUNICATION R. Gangwar, S. P. Singh, and N. Singh', *Progress in Electromagnetics Research*, 74, pp. 157–166. Available at: http://jpier.org/PIER/pier74/11.07050401.Gangwar.SS.pdf.

Gare, O.B., Lolowang, J. and Polii, J. (2022) 'Pengembangan Modul Praktikum Deviasi Dan Indeks Bias Prisma Berbasis Laboratorium Virtual', *Charm Sains: Jurnal Pendidikan Fisika*, 3(1). Available at: https://doi.org/10.53682/charmsains.v3i1.150.

Green, P.D. (2010) 'Progress In Electromagnetics Research, PIER 102, 337–350, 2010', pp. 337–350.

Hasanah (2009) 'Revolusi Dunia Telekomunikasi Dengan Serat Optik', *Jetc*, 4(1), pp. 613–626.

Hasegawa, A. (2022) 'Optical soliton: Review of its discovery and applications in ultra-high-speed communications', *Frontiers in Physics*, 10(November), pp. 1–5. Available at: https://doi.org/10.3389/fphy.2022.1044845.

In, O.S. and Fibers, O. (2015) 'Optical Solitons in', (2), pp. 371–403.

Kieu, K. (2011) 'Solitons in optical fibers What is a soliton ?', *Russell The Journal Of The Bertrand Russell Archives* [Preprint].

Kivshar, Y.S., Agrawal, G.P. and Agrawal, G.P. (2003) 'Optical Solitons: From Fibers to Photonic Crystals', *Optical Solitons: From Fibers to Photonic Crystals*, pp. 1–540. Available at: https://doi.org/10.1016/B978-0-12-410590-4.X5000-1.

Li, G. *et al.* (2024) 'Analysis of the Influence of Refraction-Parameter Deviation on Underwater Stereo-Vision Measurement with Flat Refraction Interface', *Remote Sensing*, 16(17), p. 3286. Available at: https://doi.org/10.3390/rs16173286.

'Metode_Penelitian_Soliton (1)' (no date).

Mitschke, F., Mahnke, C. and Hause, A. (2017) 'Soliton content of fiber-optic light pulses', *Applied Sciences (Switzerland)*, 7(6). Available at: https://doi.org/10.3390/app7060635.

Mukhlis, M.A., Lesmono, A.D. and Nuraini, L. (2021) 'Analisis Hubungan Indeks Bias Dan Intensitas Cahaya Pada Berbagai Fluida', *Jurnal Pembelajaran Fisika*, 10(4), p. 150. Available at: https://doi.org/10.19184/jpf.v10i4.27722.

Pebrianti, Y.H. and Kunci, K. (2006) 'YANG DIDASARKAN PADA BIT RATE , AMPLIFIER SPACING , INTERAKSI SOLITON , DAN TIMING JITTER ( ANALYSIS OF SOLITON-BASED COMMUNICATION SYSTEM LIMITED BY BIT RATE , AMPLIFIER SPACING , SOLITON DALAM SERAT OPTIK Perkembangan kinerja sistem komunikasi serat optik hingga kini telah mencapai lima generasi dimana pada generasi yang terakhir diperkenalkan konsep soliton . Pada sistem komunikasi serat optik , soliton merupakan pulsa non-dispersive adalah rugi-rugi transmisi dan lebar pita transmisi . Rugi-rugi transmisi disebabkan disebabkan oleh dispersi serat optik . Jadi dispersi merupakan pembatas kapasitas dispersi sangatlah sulit . Untuk mengatasi hal tersebut , digunakan efek non linier yaitu ketergantungan indeks bias pada intensitas gelombang cahaya . Efek non linier tersebut dapat menyebabkan perubahan spektral pulsa optik . Bila dilakukan kombinasi yang = permitivitas ruang hampa'.

Prabowo KA, A. and Ambarini, R. (2022) 'Code Switching and Its Implications for Teaching in the English Language in Math Lessons by Early Childhood Education Teachers', *KnE Social Sciences* [Preprint], (January). Available at: https://doi.org/10.18502/kss.v7i19.12428.

Prakoso, R.P., Wahyudi, E. and Masykuroh, K. (2021) 'Optimalisasi Bit Error Rate (BER) Jaringan Optik Hybrid Pada Sistem DWDM Berbasis Soliton', *Journal of Telecommunication, Electronics, and Control Engineering (JTECE)*, 3(2), pp. 62–70. Available at: https://doi.org/10.20895/jtece.v3i2.320.

Retna Apsari, Noriah Bidin, S. (2008) 'Performance of Holography Interferometer Based on Optical Reconstruction as Alternative Dental Imaging for Artificial Tooth Morphology'.

Sahelay, A., Ahirwal, R. and Jain, Y.K. (2012) 'Timer-Based Location Management to Improve Hit Ratioin Cellular Network Using Cache Memory', *International Journal of Information and Education Technology*, 2(5), pp. 494–497. Available at: https://doi.org/10.7763/ijiet.2012.v2.188.

Saleh, H., Hany, M. and Aly, M.H. (2010) 'AFBG for dispersion compensation in transmission: effect of parameters of the two beam interference fringe technique', *Photonics North 2010*, 7750, p. 77502A. Available at: https://doi.org/10.1117/12.871388.

Saputra, N., Ripai, A. and Abdullah, Z. (2022) 'The Bilinear Formula in Soliton Theory of Optical Fibers', *Jurnal Fisika Unand*, 11(3), pp. 387–392. Available at: https://doi.org/10.25077/jfu.11.3.387-392.2022.

Shahadatul Aini Binti Zainudin, M. (2012) 'Characteristics of Solitary Wave in Fiber Bragg Grating'.

Siahaan, T.F. (2015) 'Penentuan Gelombang Soliton Pada Fiber Bragg Grating Dengan Menggunakan Metode Step-Split', *Jom Fmipa*, 2(1), pp. 212–218.

Sukmayadi, D. (2014) 'PENELITIAN FUNDAMENTAL LAPORAN EVALUASI DIRI PROGRAM STUDI', pp. 1–43.

Ummah, M.S. (2019) 'No 主観的健康感を中心とした在宅高齢者における 健康関連指標に関する共分散構 造 分 析Title', *Sustainability (Switzerland)*, 11(1), pp. 1–14. Available at: http://scioteca.caf.com/bitstream/handle/123456789/1091/RED2017-Eng-8ene.pdf?sequence=12&isAllowed=y%0Ahttp://dx.doi.org/10.1016/j.regsciurbeco.2008.06.005%0Ahttps://www.researchgate.net/publication/305320484_SISTEM_PEMBETUNGAN_TERPUSAT_STRATEGI_MELESTARI.

Yasin, M. (2016) 'Pengembangan Teknologi Sensor Serat Optik untuk Menuju Kemandirian Bangsa', *Airlangga University Press*, pp. 1–64.

Zen, F.P., Hidayat, W. and Shiddiq, R. (2002) 'Analisis Numerik Propagasi Soliton Dalam Serat Optik', *Kontribusi Fisika Indonesia*, 13(2), pp. 114–120.

Zulfitri (2022) 'Analisis penggunaan dompet digital aplikasi dana dalam transaksi sehari-hari pada mahasiswa prodi pendidikan teknologi informasi uin ar-raniry banda aceh', *Skripsi, UIN Ar-Raniry Darussalam Banda Aceh*, pp. 1–79. Available at: https://repository.ar-raniry.ac.id/id/eprint/29841/1/Zulfitri, 150212107, FTK, PTI.pdf.