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Research article

Fabrication of biodegradable films using L-lactate as a chiral material to produce circularly polarized light

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Abstract: Optical activity and its relation to molecular chirality are significant in the measurement of optical rotation or circular dichroism characteristics to determine the absolute configuration of a chiral molecule. A quarter-wave plate, which is usually made from quartz, can convert linearly polarized light into circularly polarized light. In this study, we suggest using L-lactic acid (L-LA), a chiral material, and a water-based transparent glue to produce biodegradable films. Adjusting the number of thin layers, which are deposited from the mixture of L-LA and polyvinyl alcohol, leads to different phase differences, forming L-LA films. A modified microscope system was used to observe the appearance of the L-LA wave plates. Six layers and 0.8% L-LA solution were the optimal conditions to fabricate an L-LA film. The circular polarization experiment showed that the changes in maximum and minimum light intensity were within 2% compared to the average light intensity at a specific angle of the L-LA film. The performance of the L-LA film was consistent with that of a commercial quarter-wave plate. In conclusion, circularly polarized light was successfully produced using the L-LA film. The biodegradable L-LA film has widespread application in the field of biomedicine. Featured Application: L-Lactic acid film uses biodegradable and biocompatible materials. It can produce circularly polarized light and is beneficial for application in biomedicine.

Keywords: quarter-wave plates; circularly polarized light; L-lactic acid; biodegradable

1. Introduction

A wave plate is an optical device that can alter the polarization state of a light wave. In general, two types of wave plates are used: a half-wave plate and a quarter-wave plate. The half-wave plate can shift the polarization direction of linearly polarized light, whereas the quarter-wave plate can convert linearly polarized light into circularly polarized light. Circularly polarized light is used in various applications, such as navigation satellite systems, 5G wireless communication, and underwater imaging [1–3]. Owing to the extensive development of polarization-based optics, circularly polarized light has been progressively applied in biomedical sciences. For example, circular dichroism (CD) spectroscopy is an analytical method used to study the secondary structures of proteins [4]. The Stokes vector of backscattered light depicted on a Poincaré sphere can be used to detect cancerous tissues [5]. Polarization-sensitive optical coherence tomography, which has been extended to full three-dimensional (3D) imaging at high speed and sensitivity, can be used in disease diagnosis [6–8].

The quarter-wave plate can be made of natural birefringent or form birefringent material, such as birefringent crystal, liquid crystal, polymer film, and subwavelength grating [9–12]. Usually, quartz is used because of its high damage threshold and retardation stability. Sometimes, polymer wave plates are employed owing to their high adjustability. Recently, chiral inorganic nanocomposites have also been developed as materials for circular polarized light emission, and this application is actively developed [13]. However, there is a need to develop wave plates based on biodegradable or biocompatible materials for more advanced applications in the field of biomedicine. Considering the application of chiral materials in circularly polarized photodetectors [14], chiral materials can be developed into wave plate materials owing to their optical activity. In this study, L-lactic acid (L-LA) was used to prepare quarter-wave plates. L-LA is a chiral molecule and metabolite in the human body. Moreover, lactic acid bacteria can produce a large amount of L-LA, it is an easily obtainable material [15].

2. Materials and methods

2.1. Materials

L-LA was purchased from Sigma-Aldrich (St. Louis, Missouri, USA). Polyvinyl alcohol (PVA) was bought from First Chemical Works (Taipei, Taiwan). A linear polarizer and quarter-wave plate were purchased from TECH-SUN ELECTRON Co., Ltd. (Taipei, Taiwan). The circular polarizer film, CP75, was purchased from 3Dlens (Taipei, Taiwan). A microscope, TFB-6V, was purchased from ZAK-TECH (Taichung, Taiwan). A 532 nm laser was purchased from Soon-Link Co. Ltd. (Taipei, Taiwan). A photometer, TES-1337B, was purchased from TES-Electrical Electronic Corp. (Taipei, Taiwan). A power meter, PM100D, was purchased from THORLABS (New Jersey, USA).

2.2. Fabrication of L-LA films

The L-LA films were composed of L-LA and PVA. They were prepared using the following procedure: Suitable concentrations of the L-LA solutions were prepared in H_2O. The L-LA solution (17 μL) was mixed with oversaturated PVA (8 μL), and the mixture was degassed via sonication. Thereafter, 25 μL of the mixture was injected into a 4 mm diameter mold made using a 3D printer. After solidification, a single-layer biocompatible film was formed. Depending on the experiment, multilayer biocompatible films were prepared by repeating the procedure.

2.3. L-LA film modification

The L-LA film modification was conducted using a modified microscope system. The system design is illustrated in Figure 1. The traditional biological optical microscope was used as the main body. The first linear polarizer was fixed between the light source and microscope carrier, and the second linear polarizer (analyzer) was fixed between the microscope carrier and the objective lens. The L-LA film was placed on the microscope carrier. The images were captured using a charge-coupled device (CCD). Both appearance of sample and the angle of the analyzer were observed by this system. Before placing the sample, the analyzer was adjusted until the vision under the CCD was dark. After setting on the L-LA film, the analyzer was rotated until the screen of CCD was dark, and the angle between L-LA film and analyzer was recorded.

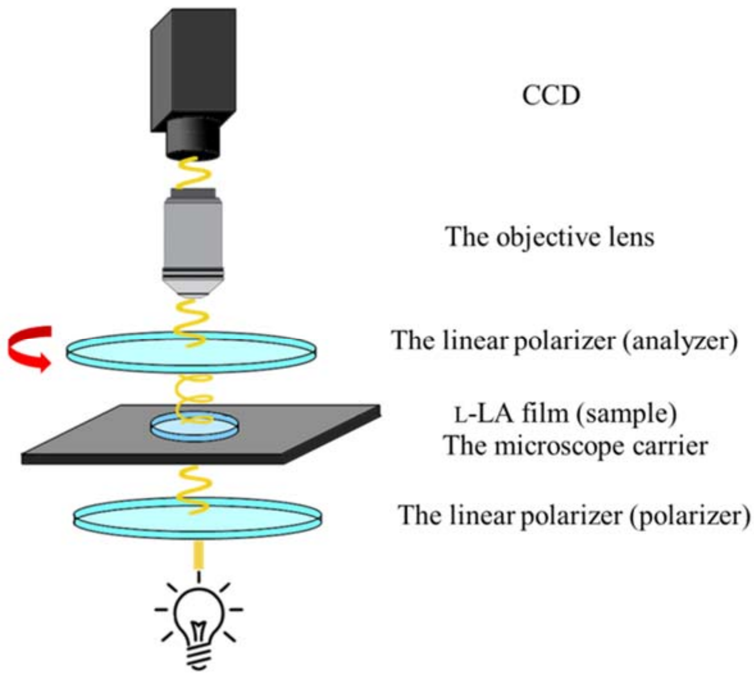

Figure 1. Schematic of the system for observing the appearance and optical rotation.

2.4. Circular polarization experiment

The system used for the circular polarization experiment is shown in Figure 2. The light source was a 532 nm laser, and the diameter of laser spot was smaller than 0.3 cm. The laser sequentially penetrates the first polarizer (polarizer), L-LA film, and second polarizer (analyzer). Then, the signal was recorded by the power meter. In this experiment, the angle between the polarizer and L-LA film was set at 0° in the beginning. The signal intensity determined by the power meter was recorded by rotating the analyzer every 10° Whenever the polarizer was rotated 10°, the signal intensity was recorded by rotating the analyzer every 10° again.

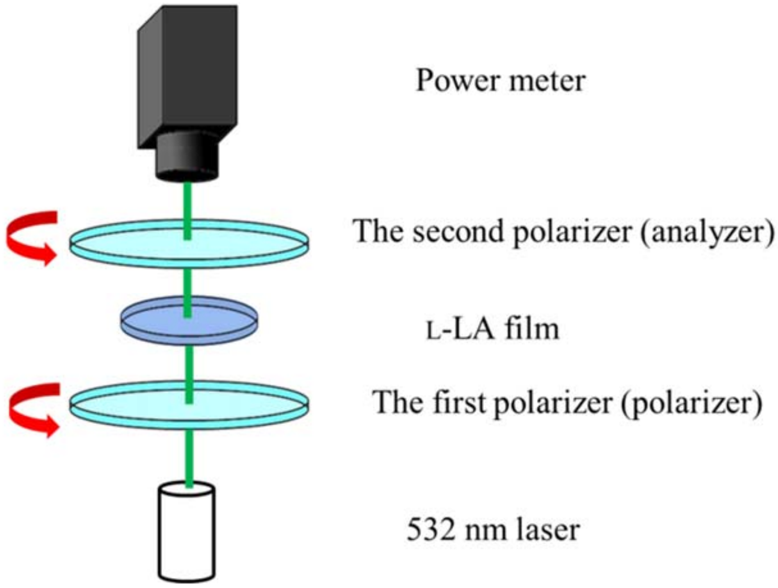

Figure 2. Schematic of the system used for the circular polarization experiment.

2.5. Comparing the function between a commercial quarter-wave plate and L-LA film

The modified microscope system is shown in Figure 3. In this system, the white light sequentially penetrated the circular polarizer film, sample (L-LA film or commercial circular polar plate), and second polarizer (analyzer). Light signals were detected using a photometer. The change of light intensity was recorded under L-LA film or commercial quarter-wave plate conditions with the rotation of analyzer.

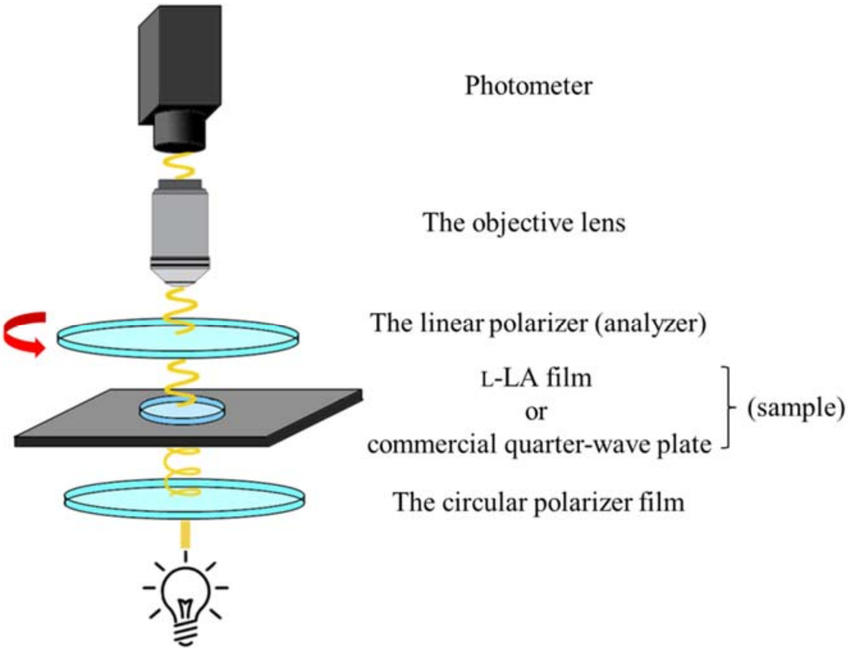

Figure 3. Schematic of the system for comparing the function between the commercial quarter wave plate and the L-LA film.

3. Results and discussion

In this study, the two conditions that were varied during this experiment to determine the optimum conditions for the L-LA films were: 1) the concentration of the L-LA in the PVA solution and 2) the number of layers deposited onto a film. Figure 4 showed that the change in the concentration and number of layers influences the optical rotation. As the concentration increased, the optical rotation of the L-LA film increased. The R^2 value of linear regression was 0.9632. The optical rotation also increases with an increase in the number of layers. The R^2 value of linear regression was 0.9996. Changing the number of layers resulted in better linear regression than changing the concentration, and we wanted to reduce the influence of PVA. Therefore, 0.8% of L-LA was fixed, and the number of layers was changed in the subsequent experiments.

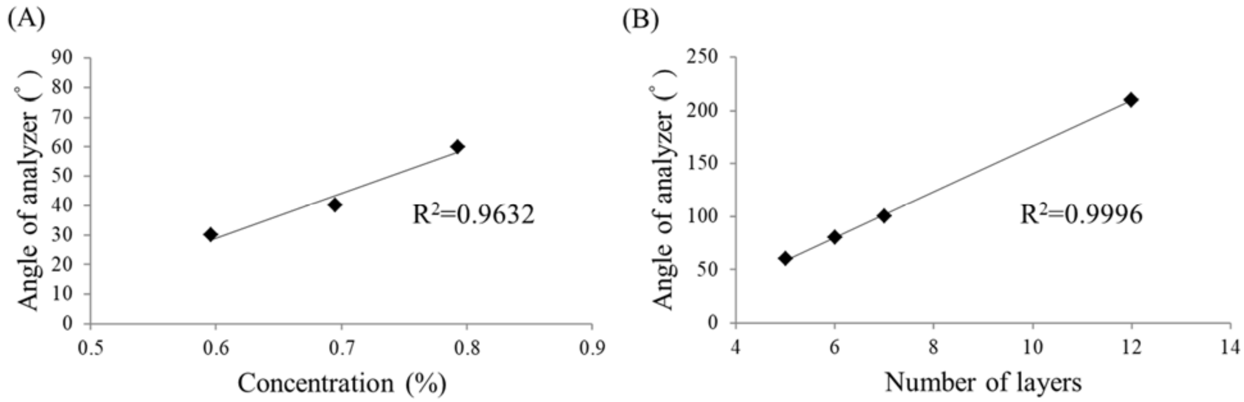

Figure 4. Influence of the change of concentration and number of layers on optical rotation.

The appearance of L-LA films in five layers, six layers, seven layers, and twelve layers were shown in Figure 5. The thickness of six layers L-LA film was 100 μm. The parts, which were circled in yellow, stayed bright in the six layers and twelve layers. It means that circularly polarized light can pass through the L-LA film stably regardless of the angle of the L-LA film. This is the characteristic of a wave plate. On the other hand, the appearance images in Figure 5 show that the L-LA films were not uniform. This might be associated with the low precision of the molds made using a 3D printer or microcrystals with different orientations in the L-LA film. This is a limitation of this study. However, in further experiments, the L-LA film still showed good circular polarization characteristics. Figure 6 shows the results of the light intensity changes when the angles of the L-LA film were 30°, 70°, and 170°, and Table 1 presents the detailed results from 0° to 180°. Importantly, when the angle of the L-LA film was 30°, the changes in maximum and minimum light intensity were within 2% compared to the average light intensity. Because circularly polarized light can pass through the linear polarizer without intensity change at any angle, this result suggests that the L-LA film has the ability to form circularly polarized light. Furthermore, the light was linearly polarized when the angle of the L-LA film was 170°. The light was elliptically polarized when the angle was 70°. This indicates that the L-LA film possesses orientation-sensitive characteristics. This behavior is similar to that of wave plates constructed from birefringent materials [9]. In a previous study, a poly L-LA drop exhibited orientation-sensitive birefringent properties. It highly depended on the orientation of lamellar crystals [16]. Because L-LA is a monomer of poly L-LA, the L-LA film could form circularly polarized light.

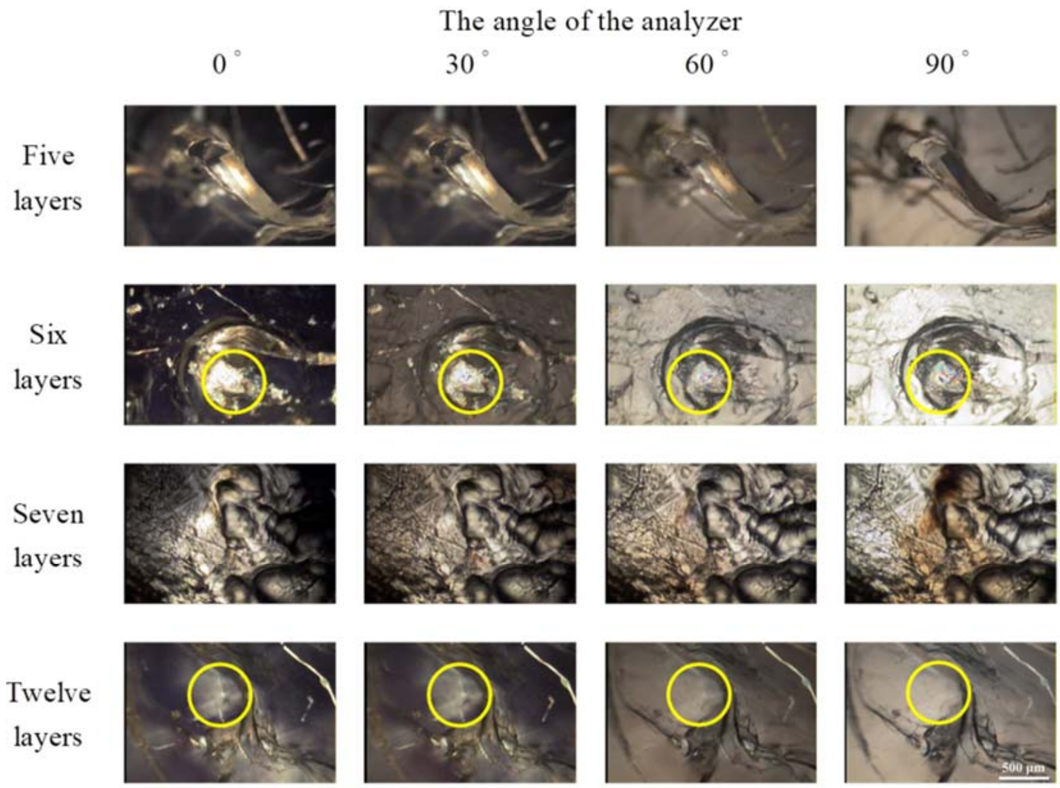

Figure 5. The appearance of L-LA films in five layers, six layers, seven layers, and twelve layers. (Yellow circle: the part stays bright) (100×).

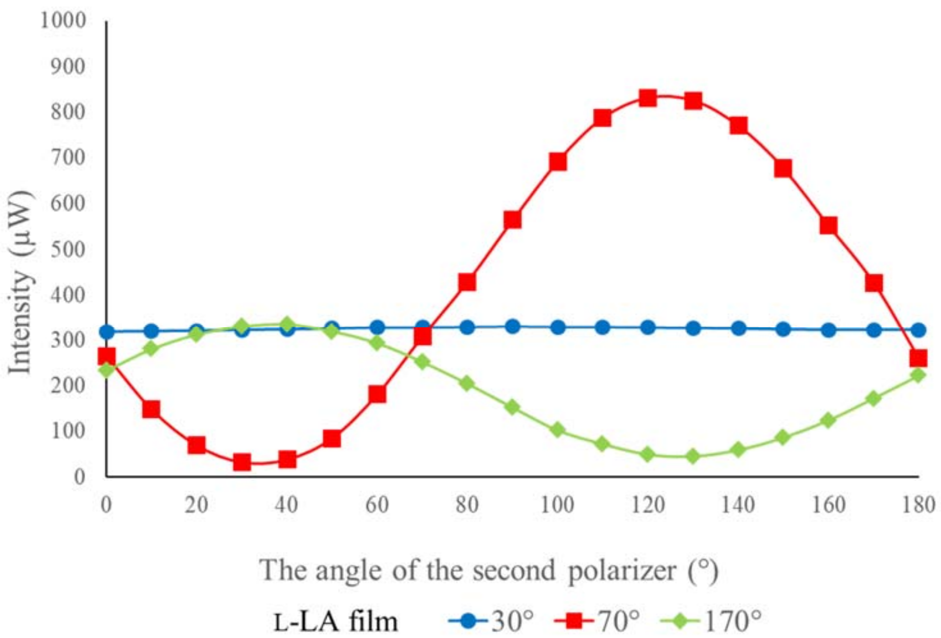

Figure 6. Scatter plot of the light intensity with respect to a change in the analyzer angle at 30°, 70°, and 170° of the L-LA film.

Table 1. Light intensity at different angles of the L-LA film and the second polarizer. Intensity is in μW.

		Angle of the L-LA film (°)																		
		0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
Angle of the second polarizer (°)	0	212	233	319	319	300	313	270	265	276	294	294	305	279	212	217	193	22	233	236
	10	251	265	320	320	268	242	163	148	176	217	254	294	299	236	146	228	256	280	270
	20	283	291	321	321	244	176	101	69	94	151	226	286	310	253	266	249	289	312	300
	30	299	304	323	323	229	146	64	32	57	125	213	284	317	261	273	263	306	330	318
	40	299	305	324	324	228	145	64	38	61	130	218	286	316	259	271	263	310	335	318
	50	285	293	326	326	241	179	108	85	117	170	243	294	309	247	252	251	299	319	306
	60	265	269	328	328	266	238	194	181	209	246	281	305	295	225	230	224	268	293	277
	70	236	237	328	328	303	312	316	308	344	340	336	319	273	198	190	192	234	252	235
	80	192	199	329	329	341	403	435	429	460	447	393	330	253	168	153	153	188	204	200
	90	143	154	330	330	389	502	559	564	574	556	448	341	232	135	115	113	143	152	150
	100	109	122	329	329	429	589	659	692	710	646	493	350	212	110	82	81	101	102	110
	110	68	95	329	329	457	663	744	787	806	715	533	357	197	91	61	57	68	72	79
	120	55	82	328	328	471	689	787	831	851	745	557	360	190	81	50	46	50	49	63
	130	50	82	327	327	472	689	787	825	850	740	554	357	190	84	51	48	48	45	63
	140	61	97	326	326	458	660	744	770	808	694	531	350	199	98	64	64	60	59	76
	150	86	118	324	324	430	595	668	677	715	646	490	338	215	119	85	96	87	86	104
	160	114	153	323	323	395	503	556	552	597	521	447	324	235	151	119	127	121	124	139
	170	161	192	323	323	348	416	431	427	460	397	384	309	256	180	148	171	168	172	186
	180	233	155	323	323	303	336	320	260	285	299	322	294	280	215	180	211	204	222	228

To further validate the circular polarization function of the L-LA film, a commercial quarter-wave plate was used for comparison with the L-LA film. When circularly polarized light passes through a quarter-wave plate, it is transformed into linearly polarized light. Initially, a 532 nm laser was also used, but the data of L-LA film were not ideal. This might be because of the low penetration rate of the circular polarizer film and the L-LA film in the system of Figure 3. Therefore, white light was used in the microscope system because it contains a wider range of wavelengths. Figure 7 shows the lumen variation of the commercial quarter-wave plate and L-LA film. The result of the L-LA film was similar to that of the commercial quarter-wave plate. This proves that the L-LA film has the function of circular polarization.

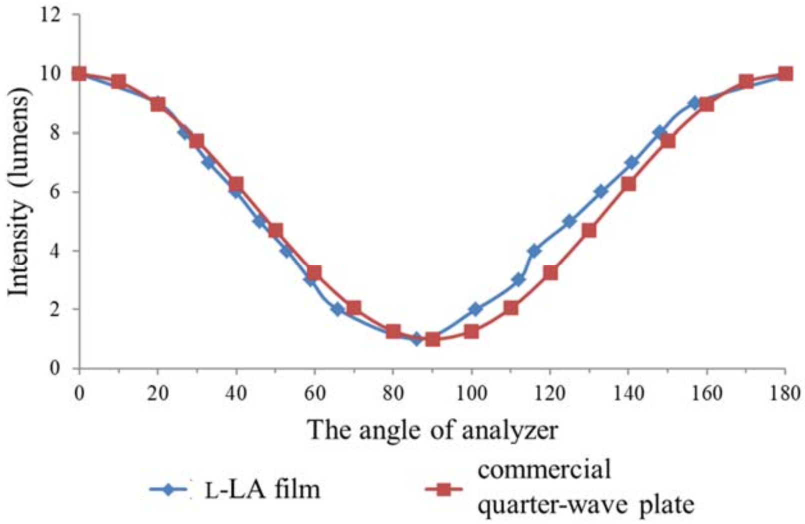

Figure 7. Comparison of the circular polarization ability of the L-LA film with the commercial quarter-wave plate.

From the materials, the L-LA film was composed of L-LA and PVA. PVA is a water-based transparent glue with low toxicity and high biocompatibility [17,18]. It is a stable material, but degrades slowly in nature [19]. Therefore, PVA is widely used in biomedicines, cartilage replacements, and contact lenses [20,21]. In contrast, L-LA can be produced from pyruvate via lactate dehydrogenase in humans and is eliminated in urine [22,23]. In recent decades, lactic acid derivatives have been developed as biomaterials. For example, polylactic acid is used in cardiovascular devices, and chitosan lactate is used as a wound dressing [24,25]. These reports assert that the L-LA film is a biodegradable and biocompatible product.

L-LA film has high flexibility, including changing the number of layers and concentration of L-LA. L-LA film could be applied in not only the optical range but also the microwave range. Recently, circularly polarized radiations for biomedical telemetry were widely studied. Fan *et al.* miniaturized circularly polarized antenna for in-body wireless communications [26]. Kaim *et al.* used a coplanar waveguide-fed ultra-miniaturized patch antenna to induce circularly polarized radiation. The antenna shows good performance for different tissue properties [27]. Blauert and Kiourti used quarter-wave plates to modify a bio-matched antenna without loss of generality [28,29]. Depolarization of circularly polarized light scattered from biological tissues can provide valuable information for differentiating cancer tissues concealed in healthy tissues [30]. Biodegradable sensors have a unique opportunity for temporary medical implants for continuous body condition monitoring and *in vivo* sensing [31]. Thus, highly flexible L-LA film provides a choice for implantable medical devices.

4. Conclusion

We used biodegradable and biocompatible materials, L-LA and PVA, to fabricate films. Circularly polarized light was successfully produced by the L-LA films, and the L-LA films showed orientation-sensitive characteristics. The L-LA film, with biodegradability and biocompatibility, is beneficial and possesses significant potential for application in biomedicine.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Formal analysis, Po-Yeh Lin; Investigation, Jen-Ai Lee; Methodology, Chien-Ming Chen and Yu-Chia Cheng; Project administration, Chien-Ming Chen and Jen-Ai Lee; Visualization, Yu-Chia Cheng; Writing – original draft, Po-Yeh Lin; Writing – review & editing, Chien-Ming Chen.

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