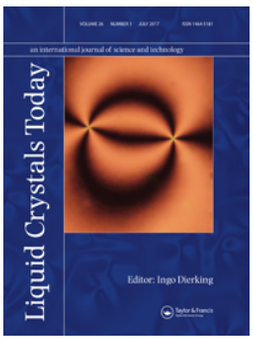

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Polymer-dispersed liquid crystal technology 'industrial evolution and current market situation'

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Introduction

Polymer-dispersed liquid crystal (PDLC) belongs to a class of electrically, photonically and thermally activated technologies referred to as 'Smart Glass'. These technologies mainly include PDLC, suspended particle device (SPD), electrochromic (EC), thermochromic (TC), photochromic (PC), thermotropic (TT) and few other (micro-blinds and nanocrystals) technologies.

The PDLC technology had been invented during 1980s by two independent entities in the USA. The first invention based on *micro-emulsion* method had been patented by J. L. Fergason in 1984 [1], and later in 1987, its exclusive patent rights had been given to Raychem Corporation (USA). Raychem's spinoff company – Taliq – begun the first commercialisation of this technology since 1987, under 'nematic curvilinear aligned phase' (NCAP) trademark. During 1990–1995 period, Raychem had out-licenced its NCAP technology to 3M (USA), Nippon Sheet Glass (JAP) and Saint Gobain (EU).

The second invention was based on *phase separation* techniques and had been patented by Kent State University (KSU), Ohio (USA) under PDLC trademark in 1987 [2]. Also during 1990–1995 period, KSU had out-licenced its PDLC technology to 3M (USA), Polytronix (USA), Asahi Glass (JAP), Ajinomoto (JAP) and Snia BPD/FIAT Group (EU).

The development of these two technologies, now both referred to as PDLC, had been the subject of many academic literature and ongoing industrial developments. The industrial evolution of PDLC technology included an early progress, later decline and recent resurgence periods. Whereas the detail accounts of its early industrial history had been already mentioned elsewhere [1], in this report, we provide a brief review of these developments, as well as an update of current worldwide PDLC market evolution.

Industrial evolution

In the past three decades, PDLC technology has been industrially developed in the worldwide scale and provided commercialised products mainly as electrically switchable 'Smart Glass' in the architectural and automotive markets for privacy and security applications. These developments begun first by few large glass, plastic and chemical industries during 1990s and dominated by small companies since 2000s periods. In 1990–1995 period, the PDLC field has been the subject of an early progress, predominantly by few worldwide licensees mentioned in the Introduction. However, in this period, due to unrealistic strategies, overestimated market forecasts and high price issues, the global PDLC market did not grow according to expectations.

During 1995–2002 period, due to patent disputes between Raychem and KSU, the field experienced a period of recession. Although by 1989, Raychem had consolidated its patent position in the USA, in 1991, KSU filed oppositions to Raychem's filed patents in Japan and Europe. However, by 1995, Raychem's patents had been granted in these territories, and, consequently, KSU lost its patent own validity in Japan and Europe. This episode had resulted in reduction and even closure of commercial activities by KSU's licensees in Japan and Europe. Namely, Asahi Glass and Ajinomoto closed their commercial PDLC activities in Japan, but Snia (FIAT) continued its R&D programme in Europe. In the USA, 3M and Polytronix continued their commercial activities because the former had licence from both Raychem and KSU and the latter, who had a worldwide licence from KSU, located its commercial activities in Taiwan under its Polytron subsidiary.

The resurgence of PDLC industrial and commercial activities begun when the original Raychem and KSU patents [2,3] had been expired in 2002 and 2005, respectively. Since this period, the field had witnessed rapid growth in industrial and commercial activities by

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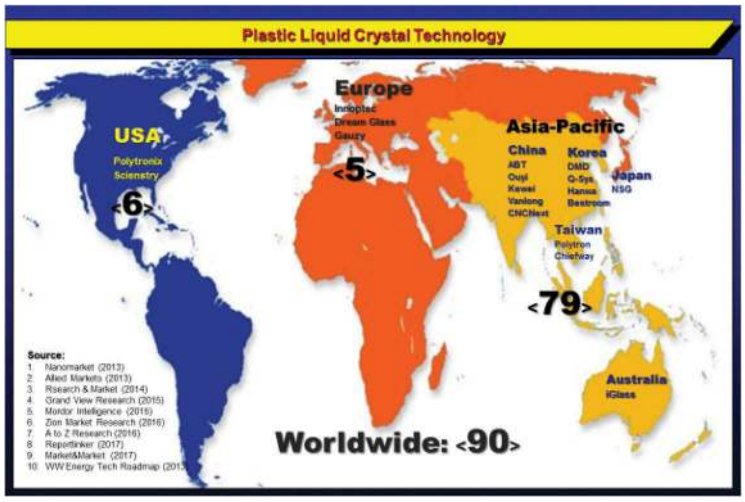

Figure 1. 2016 regional PDLC film producers and revenues.

Figure 2. Snia's first multifunctional PDLC film pilot plant.

appearance of new PDLC *film* and *glass* producers in the worldwide scene. In the past decade, due to increase in competitions, gradual reduction of production costs and product prices, increased expertise in glazing techniques, as well as extensive market promotion campaigns have resulted in a surge of market demands and continuous growth of PDLC business worldwide. The current ongoing globalisation of the technology is mainly due to the industrial awareness that R&D, product, application and business diversifications are the realistic strategies for market acceptance and growth of PDLC technology.

Market situation

In recent years, some worldwide market studies on 'Smart Glass' technologies have been appeared in the literature on automotive, construction, marine and aviation sectors. However, these reports usually do not deal with complete market situations of PDLC technology. Almost all market studies selected and cited in this report [4–12], only deal with few PDLC *film* and *glass* producers. Consequently, in the absence of a dedicated study in this field, none of the available literature provides reliable global market forecasts on PDLC technology. Such shortcoming is due to, from one hand, the lack of an independent report and, from other hand, the continuous evolution of PDLC film and glass producers in the worldwide market.

Consequently, for the time being, we attempt to provide the most reliable PDLC's global market situation in 2016, based on the mean values of the existing market forecasts [4–12]. Accordingly, the worldwide market value of total 'Smart Glass' (including PDLC, SPD, EC, TC, TT and PC) has been around $2.6 billion in 2016 and is expected to reach over $8 billion by 2022. Also, the Smart Glass market shares were estimated to be around $1.0 billion in Europe/Mideast, $1.0 billion in the Americas and $0.6 billion in Asia-Pacific regions. The Compound Annual Growth Rate values in these forecasts are widely variable within 9–21% range, which provides an overall confidence margin of around 80% of these studies.

According to the present scheme, the global PDLC technology market share in 2016 is around 14% of total

Table 1. Worldwide manufacturers of PDLC film in 2016.

Company	Country	Product	
Nippon Sheet Glass	Japan	UMU	
DMDisplay	Korea	Magic Screen	
Hanwha	Korea	PolyDreamer	
Bestroom	Korea	PDLC Smart	
Kewei	China	Smart VU	
Ouyi	China	OYPDLC	
ABTech	China	STF	
CNCnext	China	CNC-Smart	
InnoGlass	China	Smart Film	
Chiefway	Taiwan	PDLC Film	
Polytron	Taiwan	Polyvision	
	USA		
Polytronix		Texas	Polyvision
Scienstry		Texas	3G-SF
	EUROPE		
Innoptec		Italy	LPF
Dreamglass		Spain	Privacy Glass
Gauzy		Israel	LCG

Smart Glass market and results in around $90 and $360 million annual revenues for PDLC *film* and *glass*, respectively. However, as the cited market studies [4–12] do not consider all commercial producers of PDLC *film* and *glass*, their actual market values should be larger than the above-mentioned estimations.

It should be noted that the knowledge of PDLC *film* manufacturing situation is essential for better understanding of its worldwide status. Accordingly, in Table 1, we tabulated the current worldwide manufacturers of PDLC *films* at three principal regions of Asia-Pacific (China, Japan, South Korea, Taiwan and Australia), Europe (Italy, Spain and Israel) and the USA. It should be noted that the present work does not deal with PDLC *glass* market because this market consists of large numbers of globally diverse glazing manufacturers, processors, distributers, resellers and traders, which requires a separate market study.

In Figure 1, we present the current global PDLC *film* manufacturers (see Table 1), as well as their regional market revenues in 2016. From Figure 1, it is noticed that over 85% of PDLC *film* manufacturers and sales revenues ($79 million) are in Asia-Pacific, while nearly 70% of its markets are in the Americas, Europe and Middle East regions. Such disparity between PDLC *film* market consumption and manufacturing through concentration of their production in the Asia-Pacific is the outcome of a series of historical factors, few of which are:

(a) Disappearance and relocation of film manufacturers during patent dispute;
(b) Appearance of new manufacturers in undisputed patent territories after 1995 and after Raychem and KSU patent expirations;
(c) Access to low-cost raw materials in the region; and
(d) Low manufacturing costs and product prices.

For example, in spite of increase in market demands, manufacturing of PDLC *film* in the USA has been drastically reduced in recent years. In late 1990s, 3M had closed its manufacturing and joint commercial activities with Marvin Windows. During the same period, Polytronix has opened new *film* production and sales in Taiwan and China, and it seems to have acquired Scienstry recently. In 2012, Citala – the last licensee of Raychem after Taliq and Xymox – had closed its activity in the USA. The major current commercial PDLC *film* suppliers to the USA market are Polytronix, DMDisplay, ABT, Gauzy and few other Asia-Pacific manufacturers (see Table 1).

In Europe, the situation has been rather different where, regardless of patent dispute period, the industrial development and successive commercial activities had increased steadily during the past two decades. During 1990s, the first European industrial development of PDLC *film* technology licenced from KSU had carried out by the author at Snia (FIAT Group). In Figure 2, we show images of Snia's first multifunctional pilot plant, capable of manufacturing both PS and ME types of PDLC *film*. Successively, this technology had been transferred to three European companies: Innoptec (2002), Dream Glass (2008) and Gauzy (2014) (see Table 1).

Conclusion

The brief review of industrial development and market situation of PDLC technology presented here suggests that this field has become the subject of worldwide demand and growth again. In particular, the recent new development and manufacturing of PDLC *film* and *glass* products in Europe are in rapid growing cycles, which are expected to become at the forefront of industrial PDLC technology in the coming decade. However, success of this field of LC technology could be further guaranteed upon active academic participation. A strong industrial–academic collaboration through new strategies of alliance, product, technology and business diversification will be able to place the PDLC in the forefront of Smart Glass technologies. Further information on industrial developments of PDLC technology in Europe will be the subject of a future report.

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