1986

Bibliometric Techniques for Monitoring Performance in Technologically Oriented Research: The Case of Integrated Optics

Diana Hicks, *Georgia Institute of Technology - Main Campus*
Ben R Martin, *University of Sussex*

Bibliometric Techniques for Monitoring Performance in Technologically Oriented Research: The Case of Integrated Optics

Diana Hicks, Ben R. Martin and John Irvine

Science Policy Research Unit, University of Sussex, Falmer, Brighton BN1 9RF, UK.

Abstract

This paper outlines a low-cost manual-scanning approach for monitoring national and organizational research performance using a range of publication and citation indicators. We present the results of a case-study on integrated optics, a subfield of optical physics with potential industrial importance in that it may lead to the development of optical analogues of integrated circuits. It is argued that the assessment approach adopted may be of value in R&D management and strategic planning for both companies and government research-funding agencies.

1. INTRODUCTION: THE NEED FOR RESEARCH MONITORING

This paper focusses on a growing concern of R&D management in both companies and research institutes — the problem of how to monitor research activities in other organizations and countries so that significant developments are identified as rapidly as possible. At the heart of this demand for better research intelligence is the recognition that the important new basic technologies (for example, information technology, biological materials and processes, and microelectronics) are all highly science-dependent, and that intellectual capital will play a far greater role in maintaining industrial competitiveness than hitherto. While much of the scientific base of these technologies is already in place, the realization of their full commercial potential still depends on successfully implementing the results of current and future basic research. As a result, the interface between academic research and industrial R&D has assumed greater significance, with specialties previously funded on a curiosity-oriented basis by national science foundations increasingly finding themselves drawn upon by firms attempting to further their longer-term technological programmes. Science-based companies in particular clearly need to be aware of research developments worldwide if they are to maintain the ability to carry out front-line R&D.

2. APPROACHES TO GATHERING RESEARCH INTELLIGENCE

No single method is adequate for obtaining good research intelligence, as is evident from the wide variety of approaches adopted by large high-technology corporations in Japan (see Irvine and Martin, 1984, pp. 124–32). Among the mechanisms used by firms (and indeed research institutes) to monitor scientific developments are the following:

1. on-line access to major research literature data-bases and support of good in-house library and information services;
2. regular commissioning of state-of-the-art research reviews by specialized consultancies, and subscriptions to relevant multi-user studies;
3. flexible recruitment of staff with skills relevant to emerging research areas (for example, from academe or industrial competitors);
4. support of sufficient in-house basic research to enable staff to remain at or near the forefront in the field, taking part in the crucial process of informal knowledge-transfer (exchange of pre-prints, attendance at invited specialist conferences, and continuous and open

access to scientific peers, including researchers in other companies);
5. retaining as consultants senior staff in leading university departments working in important research areas.

In what follows, we shall concentrate on methods for systematically monitoring the publicly available research and patent literature. Over the last decade, the increasing capacity to store and process large volumes of data has encouraged the growth of information services providing systematic technological intelligence to firms and others. Most importantly, certain US consultancy organizations have developed novel approaches to monitoring research activity which are currently being taken up by government and industry. One of the more successful is CHI Research which has constructed a unique data-bank on US patents, including those taken out by foreign firms. In addition to information on the innovating firm and the characteristics of the invention, CHI includes data on the references contained in each patent-application both to previous relevant patents and to research papers reporting results on which the invention is based. By examining the interrelation of heavily 'cited' patents, one can construct 'maps' of technological domains and assess the relative position of different companies (or countries) within each domain. Such information is sold to firms and others for use in strategic research-planning (Carpenter et al., 1981; Narin, 1983; Narin et al., 1984), enabling them to keep track of 'hot' technological areas (see also a related study by Lieberman (1978) on science-technology coupling in electronics).

Analyses have also been carried out by CHI Research relating patents to earlier basic research, identifying for given patent classes the areas and types of research providing important inputs to patent applications. For example, in the case of 383,000 US patents registered between 1975 and 1980, some 40 per cent of the citations to scientific research were to chemistry, while physics accounted for just 13 per cent (Carpenter, 1983, p. 24). Certain industrial sectors also depend more heavily on science than others: defence-related companies, for example, are apparently more than twice as dependent on the scientific literature as other firms, and rely particularly on applied physics, electronics and solid-state physics (private correspondence with CHI Research, 1983). Furthermore, it has been found that many patents cite very recent research: the average age of cited papers is around five years but much less in areas like electronics and biochemistry (cf. Carpenter and Narin, 1978; Carpenter et al., 1981).

A second consultancy company compiling computerized data for planning and managing R&D is the Center for Research Planning (CRP). CRP has a joint-venture agreement with the Institute for Scientific Information (ISI) to exploit the latter's publication and citation data-bases for policy purposes. ISI scans half a million papers annually in approximately 3000 of the world's leading scientific journals (although the coverage is biased towards English language countries). For each paper, the references to previous research articles are abstracted and recorded on computer. Of the three main sections to the *Science Citation Index* (published annually by ISI), one lists by author all papers published that year in the journals scanned, while a second lists the papers by institutional affiliation of their first-named authors. Using such information on publications, one can obtain an indication of the relative scientific outputs of particular research groups, universities or laboratories.

The third section of the *Science Citation Index*, however, has perhaps the greatest potential for strategic management of research. This lists the articles referred to or 'cited' by the 500,000 papers published and scanned that year. One can therefore establish for particular papers the scientists who have referred to them during the year and the total number of times they have been cited. If it is assumed that the authors of scientific papers are, through the act of referring to other articles, acknowledging some form of intellectual debt, then citation analysis can be used to determine which research papers (or scientists or laboratories) have had most impact on the work of other scientists in a given year (cf. Garfield, 1979).

An alternative approach, termed 'co-citation analysis', starts from a slightly different assumption that, if two articles are both referred to, or 'co-cited', in a third paper, then an intellectual link exists between them. It is further assumed that the more frequently two articles are cited together, the stronger is this link. By identifying the most frequently co-cited papers in a particular research field, and 'mapping' them (using computerized clustering techniques) according to their frequency of co-citation (i.e. the papers most frequently co-cited are placed closest together on the research map), one can produce, it is claimed, a 'model' of the intellectual structure of the field concerned. Furthermore, by comparing the cognitive map for one year with that for subsequent years, one can perhaps identify rapidly changing research areas within a field (CRP, 1983; 1984).

While such specialized consultancy services have become increasingly valuable in providing corporate technological intelligence, it is clear that they are of greatest utility when there already exists an in-house capability to interpret the results and to carry out more specific studies. This is especially true when the information required is of a relatively general or exploratory nature, or where the organization has little prior experience in the field. In such cases, the costs of commissioning computer-based studies may not always be justifiable.

In what follows, we outline a manual approach to mapping a research area worldwide which can be used either prior to commissioning a computer-based study, or as a parallel source of data. This can be carried out relatively easily within a company (or research institute) once the basic techniques of bibliometric analysis have been mastered, and has the additional benefit that it may stimulate the development of the in-house capability necessary to exploit to the full the various consultancy services available. Previously, this approach has been used in assessing research performance in the relatively basic areas of protein crystallography and ocean currents (Martin et al., 1985). Here, we report the results of an attempt to apply the approach to a more technologically oriented research area, namely integrated optics.

3. BIBLIOMETRIC ANALYSIS OF INTEGRATED OPTICS

Integrated optics, the focus of our case-study was, for many years, typical of many research areas with likely commercial potential. The subject was and indeed still is highly interdisciplinary, drawing on specialties in physics, electronic engineering and materials science, with academic, industrial, and defence scientists all engaged in essentially similar types of work. Though having been an academic research area for some time, it is still intellectually interesting for university scientists, and therefore yields papers in professional and learned journals; in addition, it has potential industrial and military value. If optical computers are eventually adopted as the path to high-speed computing, hardware design will draw on integrated optics research. (A useful popular review of the possibilities for integrated optics is given in Senior (1985).) In the shorter-term, specialist applications are likely in high-data rate, long-distance communications (Kogelnik, 1983, p. 1), with optical integrated circuits (OICs) used to switch, amplify and couple signals in fibre-optics circuits (Hunsberger, 1982, p. 277). Because these devices can achieve ultra-short switching times, the technology may also find a variety of scientific applications — for example, "measurements of ultra fast processes in materials can be made using light beams gated with such switches" (Smith, 1984, p. 433). The technology will certainly be of military significance:

> "Probably the most significant demonstration of a multi-element OIC that has been performed to date is the hybrid implementation of the real-time rf [radio frequency] spectrum analyzer [which enables] the pilot of a military aircraft to obtain an instantaneous spectral analysis of an incoming radar beam, in order to determine if his plane is being tracked by a ground station, air-to-air missile, etc. Obviously such information is required if he is to be able to quickly take effective evasive action." (Hunsberger, 1982, p. 266)

Among the questions that a company or research institute might seek to address in a bibliometric analysis of an area like integrated optics are the following:

(i) Which countries and organizations have been most active in the area? How have patterns of activity changed over time?
(ii) What work in the open literature has had most impact, especially over recent years?
(iii) Which organizations have produced the crucial breakthroughs in the area? What were the subjects of these papers, and which scientists were involved?

3.1 ANALYSIS OF PUBLICATIONS

The first step in any bibliometric analysis is to construct a suitable publication data-base. How this task is best approached varies with the characteristics of the field under consideration and the extent of existing documentation — for example, to study protein crystallography, an already existing international data-bank was used (see Martin et al., 1985), while in an assessment of world high-energy physics a new data-base was specially constructed by manually scanning the eleven main international journals used by researchers in the field to report experimental results (Irvine and Martin, 1985).

Appraisal of the possible options for integrated optics showed that relatively complete international coverage of more basic research, as opposed to applications-oriented device and development work in integrated optics (most importantly, including contributions from Eastern Europe and Japan — regions which are often under-represented in Western information services), could be achieved by combining the papers listed under the 'integrated optics' and 'optical waveguides' sections of *Physics Abstracts* and *Electrical Engineering Abstracts*. Both abstracts are produced by the Institution of Electrical Engineers and derived from a single data-base. (Just over 3000 journals were scanned in 1983, nearly 600 of which were fully abstracted.) A list of relevant papers was compiled manually from the abstracts and the references transcribed onto file cards (a process that will in future studies be substantially shortened by entering data directly into a lap computer).

In compiling a publication list for an interdisciplinary area like integrated optics, defining the boundaries can be extremely difficult. (A relatively narrow definition of the field was used in our study consistent with the *Physics Abstracts* categories of 'integrated optics' and 'optical waveguides'. Thus, research on gallium arsenide and lithium niobate waveguide-based devices for use in the visible region of the spectrum forms the central element of the field studied. In addition, we included in the bibliography used to undertake the analysis all related work cross-referenced in the abstracts from these two integrated optics categories. This has the result that work on fibre optics (including connectors) is not included, while research on semiconductor lasers and non-linear optical materials — specialties somewhat independent of integrated optics — were not comprehensively covered, although some of the more central basic work was included. This narrow field definition needs to be borne in mind when evaluating the work of particular institutions — for example, the important work of Heriot-Watt University in the infrared region of the spectrum on devices based on non-linear materials is not recognised in this study. Because the study was carried out using a manual scanning approach, it would in principle have been possible to widen the field coverage to include more of the specialties closely allied to integrated optics.) However, in contrast to computer-based keyword searches, which tend to generate varying precentages of spurious material and rarely retrieve all literature of interest, the analyst adopting a manual-scanning approach actually reads the abstracts and so produces a higher quality data-base or one tailored to specific policy requirements. In this study, peripheral work included by the abstracting services as integrated optics was discarded by one of the authors with prior theoretical and experimental experience in the field, and aided by comprehensive review articles. Short articles published only as abstracts, books, book chapters and review articles

were likewise excluded since they rarely advance the research frontier, as also were reports based on government contract work since any significant results they contain are often republished in journal articles later on, and to include them would introduce an element of double-counting. The final list of journal articles and literature from conference proceedings should therefore contain most of the original contributions to knowledge in integrated optics.

The abstracts (or the original paper itself where necessary) provided details on the nationality and organizational affiliation of authors. Table 1 gives a breakdown of the 2519 integrated optics papers published between 1973 and 1982 by country of the first author's home institution. (Data for Bell Labs are reported separately since they constitute a large proportion of the total.) To smooth out short-term fluctuations and render long-term trends more visible, annual totals have been combined into two-year blocks. As can be seen, the US has been by far the largest producer of integrated optics papers, followed by Japan, the USSR, the UK, West Germany and France. The US has dominated publication output in every two-year block, although the absolute figure has fallen somewhat since 1977/78. In terms of its percentage share of the world total, the US has steadily declined, the gap between it and Japan narrowing markedly. Bell Labs, because it has been responsible for a fairly constant number of papers, has seen its world-share slowly decrease as the field has grown. Another feature of the table is the rapid increase in the USSR's output between 1973 and 1976 in both absolute and relative terms. Also notable is the increased participation of the 'rest of the world' in later years, largely due to the appearance of Chinese, Czechoslovakian and Polish papers.

Table 2 gives an example of how the publication data can be broken down to focus on individual research organizations within one country, in this case the UK. Over the period 1973—82, University College

Table 1: Integrated optics — publication counts[1]

	1973/74	1975/76	1977/78	1979/80	1981/82	Total
Canada	9 (3.1)	11 (2.8)	14 (2.3)	19 (3.3)	9 (1.4)	62 (2.5)
France	23 (7.8)	20 (5.1)	25 (4.1)	24 (4.2)	18 (2.8)	110 (4.4)
West Germany	14 (4.7)	18 (4.5)	17 (2.8)	26 (4.6)	37 (5.7)	112 (4.4)
Japan	47 (15.9)	76 (19.2)	128 (21.0)	95 (16.6)	131 (20.2)	477 (18.9)
UK	18 (6.1)	20 (5.1)	27 (4.4)	21 (3.7)	44 (6.8)	130 (5.2)
US (excluding Bell Labs)	107 (36.3)	141 (35.6)	202 (33.2)	178 (31.2)	157 (24.2)	785 (31.2)
Bell Labs	49 (16.6)	38 (9.6)	42 (6.9)	38 (6.6)	42 (6.5)	209 (8.3)
USSR	21 (7.1)	45 (11.4)	124 (20.4)	100 (17.5)	127 (19.6)	417 (16.6)
Rest of World	7 (2.4)	27 (6.9)	30 (4.9)	70 (12.3)	83 (12.8)	217 (8.6)
World total	295 (100)	396 (100)	609 (100)	571 (100)	648 (100)	2519 (100)

Source: Hicks (1984), Table 1.
[1] Figures in brackets are percentages of the world total.

Table 2 Integrated optics — UK organizations publishing more than one paper, 1973—82[1]

	Number of publications	Year of 1st publication
British Telecom	11 (8.4)	1977
Cambridge University	2 (1.5)	1974
Hatfield Polytechnic	3 (2.3)	1974
Oxford University	3 (2.3)	1980
Phillips	2 (1.5)	1973
Plessey	7 (5.3)	1979
Queen Mary College (London)	3 (2.3)	1977
STL	6 (4.6)	1974
University College (London)	30 (22.9)	1973
University of Glasgow	40 (30.5)	1973
University of Manchester	2 (1.5)	1975
University of Sheffield	5 (3.8)	1979
University of Sussex	4 (3.1)	1975
Other	13 (9.9)	1973
Total	131 (100)	1973

Source: Hicks (1984), Table 8.
[1] Figures in brackets are percentages of the UK total.

(London) and the University of Glasgow were clearly the main publishers, together accounting for 53% of the British total. Industrial firms produced approximately 20% of UK papers, but their share increased appreciably over time, with British Telecom and Plessey being especially active in recent years as various possible applications for integrated optics emerged and as optical computers came to be seen as offering a more promising path to high-speed computing than VLSI.

3.2 ANALYSIS OF CITATION IMPACT

Publication counts give no more than a general indication of overall research activity and output. Even then, the picture may be incomplete given that certain organizations, especially defence laboratories and firms (STL was cited as an example by researchers interviewed during the study), tend not to publish many journal articles. Equally important, some papers make a major impact on the development of the field while others have only a marginal influence. One way to examine the relative scientific impact of papers is to consider the number of times they are cited by other researchers.

Citation records for all publications in our data-base were compiled manually using the *Science Citation Index* (*SCI*) for the years

1976, 1978, 1980 and 1982. In each case, the citations received by papers published in that year and the preceding three years were recorded (citations given by authors to their own work were, however, excluded). Before discussing the results, a word of caution is needed concerning use of citation data drawn from the *SCI* since they are inherently biased against non-English language publications because of the uneven coverage of different countries' journals. Thus, while no Bell Labs paper and only five to seven per cent of other US, French and UK papers were published in journals not scanned in the *SCI*, for papers from Japan and the 'rest of the world' the corresponding figures were 17% and 22% respectively. Consequently, papers from the latter countries 'lose' a much higher proportion of their citations.

Citation data broken down by country for the period 1976—82 are given in Table 3. As with publication output, the US has been the dominant force in the field with a world-share of 66.1% (or 44.4% if Bell Labs are excluded), well ahead of Japan (15.0%), France (4.2%) and the USSR and UK (both with 4.0%). Among the more significant trends over time has been the approximate doubling of Japan's world-share of citations between 1976 and 1980 and the decline in impact of Bell Labs papers (their share of citations fell by half between 1976 and 1980 before picking up slightly again in 1982). Also noticeable is the relatively poor showing of the major European nations, the UK share in 1982 being 3.6% with France (4.1%) and West Germany (4.2%) only slightly higher.

Table 4 relates to the composite indicator of citations per paper (CPP), which is obtained by dividing total citations (less self citations) in a given year to papers published in the last four years by the number of publications during that period. One can see that the average impact of papers from Bell Labs (with a CPP of 2.30) has been by far the highest, although it has dropped markedly since 1976. (The aggregate CPP for all papers worldwide also more than halved between 1976 and 1982 for reasons that have yet to be established.)

Table 5 gives a breakdown of total

Table 3 Integrated optics citations (less self-citations) to work of preceding 3 years and current year[1]

	1976	1978	1980	1982	Total
Canada	15 (1.5)	8 (1.0)	9 (1.0)	9 (1.2)	41 (1.2)
France	54 (5.3)	34 (4.1)	27 (3.1)	30 (4.1)	145 (4.2)
West Germany	23 (2.2)	12 (1.4)	32 (3.7)	31 (4.2)	98 (2.8)
Japan	112 (10.9)	101 (12.2)	175 (20.0)	134 (18.1)	522 (15.0)
UK	34 (3.3)	39 (4.7)	39 (4.5)	27 (3.6)	139 (4.0)
US (excluding Bell Labs)	446 (43.5)	393 (47.3)	403 (46.1)	298 (40.3)	1540 (44.4)
Bell Labs	300 (29.3)	190 (22.9)	127 (14.5)	135 (18.2)	752 (21.7)
USSR	22 (2.1)	38 (4.6)	46 (5.3)	32 (4.3)	138 (4.0)
Rest of world	19 (1.9)	15 (1.8)	16 (1.8)	44 (5.9)	94 (2.7)
World total	1025 (100)	830 (100)	874 (100)	740 (100)	3469 (100)

Source: Hicks (1984), Table 2.5.
[1]. Figures in brackets are percentages of the world total.

Table 4 Integrated optics — citations per paper (CPP) (less self-citations) to preceding 3 years and current year

	1976	1978	1980	1982	National average
Canada	0.75	0.32	0.27	0.32	0.39
France	1.26	0.76	0.55	0.71	0.81
West Germany	0.72	0.34	0.74	0.49	0.57
Japan	0.91	0.50	0.78	0.59	0.67
UK	0.90	0.83	0.81	0.41	0.70
US (excluding Bell Labs)	1.80	1.15	1.06	0.89	1.18
Bell Labs	3.44	2.38	1.59	1.69	2.30
USSR	0.33	0.22	0.21	0.14	0.20
Rest of world	0.56	0.26	0.16	0.29	0.27
World average	1.48	0.83	0.74	0.61	0.85

Source: Hicks (1984), Table 3.

Table 5 Integrated optics citations (less self-citations) and CPP[1] to preceding 3 years and current year for most active UK organizations

	1976	1978	1980	1982	Total
University College London	17 (1.42)	11 (0.69)	6 (0.55)	8 (1.14)	42 (0.91)
University of Glasgow	11 (1.00)	30 (1.88)	28 (1.56)	6 (0.32)	75 (1.17)
Other	16 (1.07)	9 (0.60)	8 (0.42)	22 (0.56)	55 (0.63)
Total	44 (1.16)	50 (1.06)	42 (0.88)	36 (0.54)	172 (0.87)

Source: Hicks (1984), Tables 10—12.
[1] Figures in brackets

citations and CPP for the main organizations active in this field in the United Kingdom. One notable feature here is the pre-eminence of the two university groups at University College (London) and Glasgow, which together accounted for the bulk of UK citations and which also had somewhat higher than average CPP figures.

Perhaps the most interesting bibliometric data from the point of view of R&D management are those on highly cited papers since these provide information on major advances (see, in particular, Yermish and Drory, 1976). In the case of integrated optics, the top one per cent most highly cited papers gained fourteen or more citations in any one year and the top five per cent nine or more. As can be seen from Table 6, this indicator reveals very clearly the US dominance of the field — especially at the higher thresholds — with Bell Labs alone accounting for no less than 69% of the top 0.5% most highly cited papers. Even at the lower threshold of papers cited 9 or more times in a year, Japan, the next most successful country, accounted for well under 20% of the world total, while France and the UK produced only one such paper (0.9%) and West Germany none.

One advantage of the approach adopted here is that the data on highly cited papers can (as with publications and citations) be further broken down to the level of individual companies and research institutes. Table 7 reveals that industrial and defence laboratories produced 68 out of 112 papers

Table 6 Integrated optics — highly cited papers, 1972—82[1] (Number of publications receiving n citations in any one year)

	n ≥ 9	n ≥ 12	n ≥ 14	n ≥ 18
US (excluding Bell Labs)	50 (44.2)	24 (43.6)	9 (34.6)	3 (23.1)
Bell Labs	41 (36.3)	24 (43.6)	13 (50.0)	9 (69.0)
Japan	20 (17.7)	6 (10.9)	3 (11.5)	1 (7.7)
France	1 (0.9)	1 (1.8)	1 (3.8)	
UK	1 (0.9)			
Rest of world	0			
Total	113 (100)	55 (100)	26 (100)	13 (100)
% of all published papers	4.5	2.2	1.0	0.5

Source: Hicks (1984), Table 4.
[1] Figures in brackets are percentages of world total of highly cited papers.

(61%) cited 9 or more times in a year, and thus provides evidence that bibliometric approaches can help monitor corporate performance even in technologically oriented research areas.

From the point of view of providing corporate intelligence on a particular research field, it is also useful to have details on the research with high impact, and the researchers involved. Such information is given in Table 8 for the top 1% most cited papers (i.e. cited 14 or more times in a year). The most recent highly cited paper was published in 1979 because integrated optics papers typically achieve their peak rate of citation after two to three years. For a more current analysis, recent papers could be scanned using a lower citation threshold. (Citation data generally become available in July for the preceding year.)

Finally, Table 9 contains the results of further analysis of Japanese and US highly cited papers. Abstracts were read to determine the primary objective of each paper, these falling into three general classes: (i) producing a new or improved device; (ii) attaining new knowledge of materials or of fabrication techniques; and (iii) achieving some theoretical advance. The data suggest that Japanese work on devices and materials and fabrication techniques has had more impact than their theoretical work.

4. CONCLUSIONS: THE UTILITY OF BIBLIOMETRIC DATA

To conclude, we shall briefly consider the benefits and the weaknesses of the method outlined above for mapping research activity. There is sometimes a temptation to assume that once 'numbers' have been obtained relating to research performance, this removes the need for monitoring by other means. This temptation must be resisted. Indeed, corporate R&D management should continue to rely wherever possible on the knowledge and intuition of those of their researchers who are fully integrated into the informal system of scientific communication within the research community concerned. However, what we hope the above case-study will have succeeded in demonstrating is the following:

(1) A manual approach to bibliometric scanning can produce data on the comparative output and impact of

Table 7 Integrated optics — organizational breakdown of highly cited papers, 1972—82[1] (Organizations producing more than one highly cited paper)

	n ⩾ 9	n ⩾ 12	n ⩾ 14	n ⩾ 18
Berkeley	4 (3.6)	1 (1.8)		
Caltech	9 (8.0)	5 (9.1)	3 (11.5)	1 (7.7)
Georgia Institute of Technology	2 (1.8)			
Hughes	2 (1.8)	1 (1.8)		
IBM	3 (2.7)	1 (1.8)		
MIT	4 (3.6)	1 (1.8)		
US Navy	6 (5.4)	4 (7.3)	1 (3.8)	
RCA	4 (3.6)	3 (5.5)	1 (3.8)	1 (7.7)
Texas Instruments	2 (1.8)	1 (1.8)	1 (3.8)	
USC—LA	2 (1.8)	2 (3.6)	1 (3.8)	1 (7.7)
Washington University	2 (1.8)			
Xerox	2 (1.8)	2 (3.6)	2 (7.7)	
NTT (Japan)	9 (8.0)	3 (5.5)	1 (3.8)	1 (7.7)
Tokyo Institute of Technology	6 (5.4)	1 (1.8)	1 (3.8)	
Bell Labs	40 (35.7)	24 (43.6)	13 (50.0)	9 (69.0)
Other	15 (13.4)	6 (10.9)	2 (7.7)	
Total	112 (100)	55 (100)	26 (100)	13 (100)

Source: Hicks (1984), Table 6.
[1] Figures in brackets are percentages.

research in a particular specialty carried out within different countries and organizations.

(2) Such data can be useful both for the purposes of corporate technological intelligence and to inform R&D management in universities and government research laboratories. The data may also be of interest to research-funding agencies seeking to assess the relative standing of their country in world terms, or to monitor the activities of research groups receiving funding from them.

(3) Compiling the data is relatively easy and inexpensive, and the method yields information that is not difficult to understand or use in R&D decision-making. (The data for integrated optics required twelve person-weeks of effort, including a certain element for training purposes.)

(4) With manual scanning, those undertaking the study become immersed in

Table 8 Top 1% most highly cited papers

Year published	1st author	Organization	Theme
1972	Tien	Bell	Organic polymer thin film waveguides
1972	Tien	Bell	Iron garnet film switch and modulator
1973	Tien	Bell	Tapered edge coupler
1973	Nakamura	Caltech	Corrugated feedback laser
1973	Conwell	Xerox	Exact solution for modes in diffused guides
1973	Miyazawa	NTT	$LiNbO_3$ single crystal film grown on $LiTaO_3$
1973	Yariv	Caltech	Coupled mode solutions for di-electric waveguides
1973	Kaminow	Bell	Outdiffused, low-loss guides in $LiNbO_3$ and $LiTaO_3$
1973	Kaminow	Bell	Modulator in out-diffused $LiNbO_3$ waveguide
1973	Giallorenzi	Navy	Waveguides made by thermal diffusion of ions in glass
1974	Marcatili	Bell	Closed form, approximate solutions for rib and strip-loaded guides
1974	Schmidt	Bell	Indiffused Ti, V and Ni, $LiNbO_3$ guides
1974	Hammer	RCA	Waveguide formed by indiffusion of Nb into $LiTaO_3$
1974	Tien	Bell	Epitaxial, growth-by-melting used to grow thin-film optical waveguides and modulators
1974	Flanders	Bell	Fabrication, evaluation of corrugated grating filters in sputtered glass guides
1975	Burnham	Xerox	Laser with semicircle of GaAs surrounded by $Ga_{1-x}Al_xAs$
1975	Suematsu	Tokyo	Integrated twin-guide laser
1975	Campbell	TI	Epitaxial GaAs directional coupler
1975	Papuchon	T-CSF	Ti diffused $LiNbO_3$ switch/modulator
1976	Kogelnik	Bell	Theory of coupled waveguides with alternating phase mismatch regions (switches)
1976	Schmidt	Bell	Ti diffused $LiNbO_3$ realization of above devices
1977	Smith	Bell	Bistable optical device with differential gain
1978	Garmire	USC/LA	Hybrid multi-stable device which does not need a Fabry-Perot resonator or coherent light
1978	Smith	Bell	Fabry-Perot resonator and electro-optical element driven by transmitted light ("Optical triode")
1979	Yust	Caltech	Monolithically integrated optical repeater

Source: Hicks (1984), Table 13.

the actual content of the research literature, and can therefore better assess the contributions of individuals or organizations than those relying only on computerized (or 'remote-sensing') approaches.

Against these advantages, however, must be set the following weaknesses:

(1) Bibliometric data are frequently biased against certain nations, especially non-English language countries such as Japan. While such bias can be partly

Table 9 Contents of Japanese and US highly cited papers, 1972—82[1]

	Device	Material/fabrication	Theory	Total
US (excluding Bell Labs)	28 (56.0)	10 (20.0)	12 (24.0)	50 (100)
Bell Labs	23 (56.1)	10 (24.4)	8 (19.5)	41 (100)
Japan	11 (57.9)	7 (36.8)	1 (5.3)	19 (100)
Total	62 (56.4)	27 (24.5)	21 (19.1)	110 (100)

Source: Hicks (1984), Table 5.5
[1] Figures in brackets are percentages.

overcome by carefully constructing a representative publication data-base, analyses of impact based on citation data from the *Science Citation Index* are necessarily limited.

(2) Researchers in industry and government institutes (especially defence laboratories) differ in the extent to which they publish in the open literature. Even in a fairly basic research area where there are pressures to publish in order to achieve 'visibility' and hence ensure integration into the relevant professional community, some work may not be published.

(3) Bibliometric data generally need to be complemented by other types of information — for example, figures on patenting activity.

(4) In many cases, the results of bibliometric analysis may merely confirm the consensus view of researchers about their field (as we found when a small number of UK researchers commented upon our integrated optics findings). However, for organizations without access to a significant in-house research group or for small studies which cannot justify using large amounts of researchers' time, bibliometric analysis can provide a convenient means of generating systematic data. In addition, the data can be presented in a form accessible to those outside the specialty — for example, to officials whose task is to determine priorities between research groups and specialties competing for funds. Furthermore, both the results and the analyst's familiarity with the field gained as a by-product could be important to an organization contemplating entering a research area.

ACKNOWLEDGMENTS

The data in the study reported here were compiled by Diana Hicks as part of an MSc. thesis at the University of Sussex supervised by John Irvine and Ben Martin. The authors are grateful to the Fulbright Commission and the Leverhulme Trust for financial support. They also wish to thank Dr C. Verber (Battelle), Dr P. Laybourn (University of Glasgow), Dr M. Lewis (RSRE, Malvern), Mr K. Parker (STL), Dr G. Thompson (STL), and Dr C. Pitt (University College, London) for assistance in the study. However, none of the above individuals or organizations should be seen as endorsing, officially or otherwise, the paper's conclusions.

REFERENCES

Carpenter, M. P., (1983), 'Patent citations as indicators of scientific and technological linkages', paper presented to AAAS Annual Meeting, Detroit, Michigan, 30 May, mimeo, Cherry Hill, N.J.: CHI Research.

Carpenter, M. P. and Narin, F. (1978), *Utilization of Scientific Literature by US Patents*, Report to NSF (PRM 7801694 CHI 782-R), Washington D.C.: National Science Foundation.

Carpenter, M. P., Narin, F. and Woolff, P. (1981), 'Citation rates to technologically important patents', *World Patent Information*, 3(4), pp. 160–63.

CRP (1983), 'Literature models of science for research planning', mimeo, Philadelphia: Center for Research Planning.

CRP (1984), *ABRC Science Policy Study: Co-Citation Bibliometric Models*, Report by the Center for Research Planning to the Advisory Board for the Research Councils, Philadelphia: Center for Research Planning.

Garfield, E., (1979), *Citation Indexing: Its Theory and Application in Science, Technology, and Humanities*, New York: Wiley Interscience.

Hicks, D., (1984), *Bibliometric Assessment of Applied Research: An Empirical Study of Integrated Optics*, M.Sc. Thesis, Brighton: University of Sussex.

Hunsberger, R. G., (1982), *Integrated Optics: Theory and Technology*, Springer Series in Optical Sciences, Vol. 33, Berlin: Springer Verlag.

Irvine, J. and Martin, B. R., (1984), *Foresight in Science: Picking the Winners*, London and Dover, New Hampshire: Frances Pinter.

Irvine, J. and Martin, B. R., (1985), 'Evaluating big science: CERN's past performance and future prospects', *Scientometrics*, 7 (3–6), pp. 281–308.

Kogelnik, H. (1983), 'Integrated optics devices for optical communications', in S. Martellucci and A. N. Chester (eds.), *Integrated Optics: Physics and Applications*, New York: Plenum Press.

Lieberman, M. B., (1978), 'A literature citation study of science-technology coupling in electronics', *Proceedings of the IEEE*, 66, pp. 5–13.

Martin, B. R., Irvine, J. and Crouch, D., (1985), *Science Indicators for Research Policy: A Bibliometric Analysis of Ocean Currents and Protein Crystallography*, SPRU Occasional Paper No. 23, Brighton: University of Sussex.

Narin, F., (1983), 'New approaches to corporate technological intelligence: patent citation network', mimeo, Cherry Hill, N.J.: CHI Research.

Narin, F., Carpenter, M. P. and Woolf, P., (1984), 'Technological performance assessments based on patents and patent citations', *IEEE Transactions on Engineering Management*, EM–31 (4), pp. 172–83.

Senior, J., (1985), 'Computing with light', *New Scientist*, May 30, pp. 31–34.

Smith, P. W., (1984), 'Bistable optical devices', in D. B. Ostrowsky and E. Spitz (eds.), *New Directions in Guided Wave and Coherent Optics*, Vol. II, NATO ASI Series E, No. 79, The Hague: Martinus Nijoff.

Yermish, I. and Drory, A. (1976), 'Characteristics of highly cited papers in the engineering sciences', report submitted to the NSF in partial fulfilment of the requirements of contract C-795, mimeo, Philadelphia: Institute for Scientific Information.