PULSED LIGHT SOURCES

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FOREWORD

The extensive development of electronics and automation equipment defines the scientific and technical significance of all types of high-density energy converters that are used in electronic and automatic equipment. A powerful pulsed discharge in gas is one type of conversion of electrical energy into extremely intense optical radiation. In order to characterize the possibilities inherent in such a discharge, it suffices to recall that high-power lasers were first developed by using flashlamps based on precisely this kind of discharge.

The correct use of existing types of flashlamps, work toward developing new types of flashlamps, and the solution of new problems by using such flashlamps require a knowledge of the physical processes that occur in them and the relationship between their technical characteristics and their design data and power-supply parameters. An acquaintance with the variety of existing flashlamps and the circuits used in the equipment employing them also is needed.

This book summarizes the findings of research on the physical and technical characteristics of pulsed discharges in gases and on the implementation of such discharges in pulsed light sources, which has been conducted by the authors and their co-workers over the last few decades. In view of the lack of sufficiently complete monographs on this subject, the authors decided not to confine themselves to a presentation of their own data, but to attempt wherever possible to summarize the findings of numerous papers by other investigators which have appeared in the scientific and technical literature in recent years. We thus intended to create a needed guide to systematic acquaintance with pulsed light sources for a constantly expanding group of diverse specialists who must now develop or use flashlamps in devices in various fields of science and engineering and who must study phenomena associated with short pulses of radiation at optical wavelengths.

The first part of the book is devoted to the physical processes that occur in pulsed light sources: the triggering of the pulsed discharge and the characteristics of its high-current stage. The second part is devoted to the technical characteristics of flashlamps, the principles of their design and inductrial production, and some problems associated with their use.

The first edition of this book was published in the early 1960s [0-1]. Since then, however, our understanding of the physical processes that occur in pulsed light sources and in the design and use of such sources has deepened considerably. This is due to the current intensive development of low-temperature plasma physics as a whole, and to the less intensive development of quantum electronics, in which pulsed light sources are used as one of the principal means of optical pumping. In particular, because of this it has become possible to calculate the characteristics of pulsed sources much more accurately than when the first edition was published. We can determine the time dependence of the radiation power in a specified spectral range (from given parameters of the external electric circuit and the properties of the gas-filled gap). We also can solve the inverse problem much more effectively and comprehensively, i.e., the problem of selecting the parameters of the circuit and the gas-filled gap according to the requirements of the specific technical application of the source. Therefore, the book had to be substantially updated by including current theoretical concepts and the latest experimental data on the physical characteristics of pulsed gas discharges, as well as information on the available selection of flashlamps* and their circuit diagrams.

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* As in Reference 0-1, attention here is paid mainly to widely used pulsed light sources: flashlamps. It would be beyond the framework of the book for us to cover nonlamp-type pulsed sources specifically designed for laboratory use: discharges in the vapors of exploding metal conductors, high-power discharges with channel constriction due to the self-magnetic field, creepage over the surface of dielectrics, and others which are covered in the corresponding reviews (see, e.g., A. F. Aleksandrov and A. A. Rukhadze: "High-current discharge-type light sources," Uspekhi fizicheskikh nauk, 1974, No. 2, vol. 112, pp. 193-230; K. Fol'rat: "Spark light sources and high-frequency spark cinematography," in Fizika bystroprotekayushchikh protsessov (The Physics of High-Speed Processes), vol. 1, Moscow, Mir Publishers, 1971, pp. 96-199; S. I. Andreev, M. P. Vanyukov, and E. V. Daniel': "Surface discharge as a source of intense light flashes," Zhurnal prikladnoi spektroskopii, 1966, No. 6, vol. 5, p. 712; B. L. Borovich, P. G. Grigor'ev, V. S. Zuev, V. B. Rozanov, A. V. Startsev, and A. P. Shirokikh: "Experimental and theoretical research on the dynamics of high-power emitting electrical discharges in gases," Trudy FIAN im. P. N. Lebedev, 1974, vol. 76, p. 1; and I. V. Dvornikov, Yu. N. Kolpakov, V. A. Lakutin, and I. V. Podmoshenskii: Zhurnal prikladnoi spektroskopii, 1974, No. 2, vol. 21, pp. 227-234.

The revision affected practically all chapters, with minor changes in the general structure of the book.

In particular, new information on static and pulsed breakdown has been added in Chapter 1, which is devoted to the triggering of discharge. Instead of a separate (chapter-by-chapter) semiempirical treatment of the electrical, hydrodynamic, and optical characteristics of the plasma channel, the channel is considered as a whole in subsequent chapters on the basis of the concepts developed in recent years. Chapter 2 is devoted to processes in the expanding channel of a pulsed discharge, and Chapter 3 to the characteristics of the quasi-stationary discharge that is typical principally of tubular flashlamps. Recent data on processes near electrodes have been added in Chapter 4. Several chapters in the second part of the book describe various technical characteristics of tubular and spherical lamps: their radiative, load, and operating characteristics. These chapters, like those devoted to the industrial production and circuit diagrams of flashlamps, have been significantly supplemented with the latest data. The diversity of flashlamp applications has grown so much in recent years that describing them is beyond the framework of the book.

Most of the bibliographic references in [0-1], which pertained mainly to the history of the field, have been omitted from this edition in order to save space. The bibliography includes chiefly publications that have appeared in print since the publication of [0-1]. Earlier works are duplicated only in the most important cases, e.g., if information essential to understanding the text was drawn from them (say, the formulas derived in these papers), or if they contain a bibliography which expands on the information given here and thus is essential to today's reader.

In addition to I. S. Marshak, A. S. Doinikov (in Chapters 5 and 10), V. P. Zhil'tsov (in Chapter 7), V. P. Kirsanov (in Chapters 2 and 6), and L. I. Shchukin (in Chapters 5, 7, and 8) helped produce the new edition of the book. Chapter 3 was rewritten by R. E. Rovinskii, and Chapter 9 by V. P. Zhil'tsov and M. G. Feigenbaum.

CONTENTS

PART 2

GAS-DISCHARGE FLASHLAMPS

INTRODUCTION

Extremely high-intensity radiation is known to be required in the solution of many scientific and technical problems. The instantaneous level is more important in these problems than the average value over a prolonged period. Accordingly, a trend has appeared in technology directed toward an increase in intensity at the expense of continuity of the radiation, i.e., toward changing over to pulsed bursts of radiation. In addition to increasing the intensity, the use of pulses also opens up the possibility of pulse coding. This is significant in many problems involving data transmission and identification of pulses against a constant radiation background.

The trend toward conversion to pulsed radiation in the radio-frequency band has become evident in fields of radio engineering that developed at a relatively late date: radar, radio navigation, etc. The same trend in the optical band has led to the development of pulsed optical-radiation sources by the electric-lamp industry. "Optical radiation" includes ultraviolet, visible, and infrared rays. For brevity, such radiation sources are simply called pulsed light sources.

The relation among the attained values of power, luminance, and luminous flux of modern continuous-wave and pulsed light sources is illustrated in Table 0-1.

The data in Table 0-1 confirm the advantage of pulsed light sources in those instances of energy transfer and data transmission where either a radiation detector and data-acquisition equipment having a sufficiently short lag are used (e.g., a vacuum photocell or a photoelectric multiplier with an appropriate circuit diagram) or the transfer process itself must persist for an inherently short

Table 0-1. Comparison of the Most Powerful and Brightest Pulsed and Continuous Electric Light Sources

Type of source	Type of lamp	Peak power, kW	Peak luminance, $Mcd \cdot m^{-2}$	Peak luminous flux, klm
Continuous	Incandescent (projector) lamps	20	30	600
Continuous	Water-cooled tubular xenon lamps with vortex stabilization of discharge [0-2 and 0-2a]	500	1000	22,000
Continuous	Superhigh-pressure spherical xenon lamps [0-2a to 0-5]	30	6000	1300
Continuous	Open high-intensity arcs	100	1400	4500
Pulsed	Tubular quartz xenon lamps	200,000	10,000	10,000,000
Pulsed	Spherical xenon lamps	10,000	100,000	200,000

time (e.g., photography of a moving object or stroboscopic observation). It is this advantage which explains the trend mentioned above toward the use of pulsed radiation as a method of improving the parameters of optical equipment with light sources in the direction of increasing speeds, improved accuracy, expanded ranges, and automation of processes in the latest equipment.

Short-duration light flashes also can be produced by using a continuous source fitted with an optical shutter or by operating in a discontinuous mode (e.g., incandescent lamps operating in an overheated condition for a short period of time, or briefly overloaded xenon or mercury arc lamps [0-5a to 0-8a]). Here approximately an order-of-magnitude increase in the power of the source over its rating is tolerable. Pulsed light sources may be based on the use of a chemical reaction (one-shot lamps [0-9 and 0-10], such as electronic flashes with a metal foil that burns in an atmosphere of oxygen or fluorine, or so-called magnesium photoflashes or photoflash bombs in which a metallic powder burns instantaneously as a result of the liberation of oxygen from an oxygen-rich salt mixed with the powder, and lamps filled with a noble gas which produce a flash as a result of the shock wave produced by an explosive [0-11]). They may be based on the brief excitation of a luminescent solid (e.g., by using an electron beam [0-12]) or on a short-duration electric discharge in a gas or in the vapor of a metal: a condensed electric spark.

The specific features of a condensed spark discharge (high temperature and luminance, its ready controllability, the possibility of frequent repetition of flashes, and the comparative simplicity of the auxiliary devices) have made the last type of pulsed light sources the most widely used ones.

A spark discharge was first used as a pulsed light source in the mid-19th century, when Fox Talbot [0-13] made high-speed photographs by using an electric spark for illumination.

In our time, pulsed (spark) discharges in gases have been studied and put to use in an extremely large number of applications. Work is being done on pulsed discharges in high-voltage engineering in the areas of lightning protection and insulation. It is used as the principal method of igniting fuel mixtures: in engines, for example. Pulsed discharges are used extensively in spectroscopy to excite the spectra of ionized atoms. It plays a significant part in many switching devices used in electrical engineering, radio engineering, and electronics (discharges, trigatrons, etc.). Nuclear physics specialists also have become interested in the pulsed discharge because the instantaneous formation of a gas plasma which accompanies the discharge is now the highest-temperature physical process that can be implemented in a small volume (in contrast to explosive processes, which use short-duration chemical or nuclear chain reactions that encompass large volumes). They view it as a possible way to carry out a controlled thermonuclear reaction or at least to study the properties that govern such a reaction.

The pulsed electric discharge in gases is used most extensively in a field that was among the first to find a practical application for it: the production of pulsed light sources.

Up until the 1930s either an open spark discharge in air [0-14] or a pulsed discharge in mercury-vapor-filled tubes [0-15] was used as an electrical pulsed light source that did not find its way outside the laboratory. An advance in the development of such sources was the use of pulsed discharges in tubes filled with noble gases and discharges in vapors of a metal wire exploded by a current. A start was made in the second half of the 1930s and the first half of the 1940s in the work of Laporte, Edgerton, Wulfson,† Marshak, and their co-workers [0-16 to 0-19]. The first series-produced pulsed electric-lamp devices were introduced in engineering as a result of that work. Extensive research has since been conducted in many countries, resulting in design and manufacturing developments which led to the rise of the industrial field of pulsed electrical light sources in the 1950s.

Today hundreds of such sources are produced in the most advanced countries. Among these we may list above all: (1) various tubular flashlamps with various peak flash energies (from a few joules for intracavity medical photography and portable electronic flashes, to hundreds of thousands of joules for aerial flash spotting and the optical pumping of lasers ([0-20 to 0-23]) and with various shapes of the glow volume (straight ones to produce a flat fan-shaped light beam, e.g., in lasers and cloud chambers [0-23 to 0-27]; spiral or U-shaped ones to produce a conical beam; circular ones to produce shadowless light beams; and so forth [0-23 and 0-28]); (2) stroboscopic flashlamps (strobotrons) with a flash rate up to a few kilohertz for stroboscopes and illuminators used in high-speed filming (from low-power neon strobotron-thyratrons for strobotachometers to xenon lamps with an average power of tens of kilowatts [0-23 and 0-29 to 0-32]); (3) lamps with light-signal devices (with a frequency of 1-3 Hz, a power of 10-500 W, and an operating life of up to a few million flashes [0-23 and 0-33 to 0-35]); (4) lamps with an especially short flash for photochemistry and various types of electronic equipment [0-36 to 0-38]; (5) a series of strobotrons for computer and other automatic devices (with a few watts of power and a frequency in the hundreds of hertz [0-39 and 0-40]); and so forth. At the same time, a wide variety of optical equipment using flashlamps is being produced. Here we may list various lasers, consumer electronic flashes, illuminators for high-speed, medical, biological, and other special

† Translator's note: names marked with a dagger have been back-transliterated from Russian and may not reflect correct spelling.

types of photography, various strobes, and others. Flashlamp devices are used in automation and remote control (devices with light control and data-transmission channels: remote-control optical contact devices, the "angle-number" sensors of computers, light-protection apparatus, transformer control on high-voltage DC transmission lines, thickness gages, etc.). They are used in laser radar and optical communications (cloud height indicators and other range finders, optical telephony, etc.). More and more light-signal devices using flashlamps are being produced (light tracers, beacons, navigation lights for modern high-speed long-range aircraft, and other lighting equipment used in transportation). A number of devices exist or are being developed in which flashlamps are used to produce time marks, for photographic recording, microfilming, time-lapse photography, printing, photolithography, photometry, etc. [0-23 and 0-41 to 0-45]. Several types of movie projectors with flashlamps have appeared, and these lamps have begun to be used for television transmission of motion pictures and for illumination in television studios using a scanning-beam transmission system. Work is being done on the use of flashlamps in many fields, such as photochemistry (photolysis, photosynthesis, metalworking by etching a surface precovered with a photosensitive varnish which is hardened by light at points that are not to be etched), etc. There can be no doubt that the further development of science and technology also will open up other areas for the use of these lamps.

The total production volume of pulsed light sources is characterized by the fact that, for example, Japan alone produced several dozen kinds of zenon flashlamps for a total of 3.32 million lamps in 1973 [0-46 and 0-47]. At the same time, flashlamp production has begun to acquire some stability and order in the last decade, after its previous turbulent development. Increasingly often, newly developed lamps and devices use standardized components, and the development work is reduced to moderate modification of parameters without implementing any fundamentally new physical or technical improvements. Attention is being paid to the possible standardization of flashlamps in terms of product variety, manufacturing processes, mating to other equipment, documentation, and other areas. Under these conditions an overall survey of the scientific principles of the field and of the design and manufacturing methods used in it seems entirely feasible and timely. This book is devoted to such a survey.

PART 1

PHYSICAL PROCESSES IN PULSED DISCHARGES